Study of I-V and C-V characteristics of a solar cell

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In this experiment, We verified the C-V characteristics of a solar cell which is a modified p-n junction. We observed that the capacitance of the solar cell decreases with the increasing direct current voltage, which is because of the increase in depth of the depletion region. We took measurements for both light and dark conditions and using the capacitor equations, the value of doping density and built-in voltage of the solar cell were estimated. We then measure the I-V characteristics of the given solar in two conditions, under an incandescent lamp and under the sun. We vary the voltage using a potentiometer and measure the current. We also study the affect of change in wavelength. Using the I-V plot we find out the corresponding open circuit voltage (V_{OC}) and short circuit voltage (I_{SC}). We then calculate maximum Power and power obtained and get the filling factor and compare it in the two cases.

The most incomprehensible thing about the world is that it is comprehensible.

Albert Einstein

I. INTRODUCTION

In the 19th century, it was observed that the sunlight striking certain materials generates detectable electric current - the photoelectric effect. There is one more related phenomena, the *photovoltaic effect*. For both phenomena, light is absorbed, causing excitation of an electron or other charge carrier to a higher-energy state. The main distinction is that the term photoelectric effect is now usually used when the electron is ejected out of the material (usually into a vacuum) and photovoltaic effect used when the excited charge carrier is still contained within the material. In either case, an electric potential (or voltage) is produced by the separation of charges, and the light has to have a sufficient energy to overcome the potential barrier for excitation. The physical essence of the difference is usually that photoelectric emission separates the charges by ballistic conduction[?] and photovoltaic emission separates them by diffusion, but some *hot carrier* photovoltaic devices concepts blur this distinction.

In 1839, at age 19, experimenting in his father's laboratory, French physicist Edmond Becquerel created the world's first photovoltaic cell. In this experiment, silver chloride or silver bromide was used to coat the platinum electrodes; once the electrodes were illuminated, voltage and current were generated. The first solar cell, consisting of a layer of selenium covered with a thin film of gold, was experimented by Charles Fritts in 1884, but it had a very poor efficiency. Developments kept going in background as the world entered the 20th century. In 1954, the first practical photovoltaic cell was publicly demonstrated at Bell Laboratories. And in 1958, solar cells gained prominence with their incorporation onto the Vanguard I satellite.

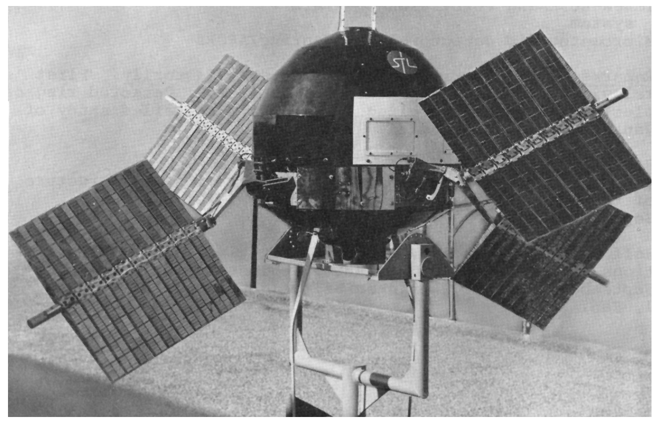


FIG. 1: NASA used solar cells on its spacecraft from the very beginning. For Example, Explorer 6, launched in 1959, had four arrays that folded out once in orbit. They provided power for months in space.

A solar cell, or photovoltaic cell, is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect, which is a physical and chemical phenomenon. It is a form of photoelectric cell, defined as a device whose electrical characteristics, such as current, voltage, or resistance, vary when exposed to light. Individual solar cell devices are often the electrical building blocks of photovoltaic modules, known colloquially as solar panels. The common single junction silicon solar cell can produce a maximum open-circuit voltage of approximately 0.5 volts to 0.6 volts.

Solar cells have far-reaching applications in the field of energy production as evident by the existence of large-scale solar farms spread across acres of photovoltaic panels, as source of power in remote locations where the transmission lines cannot reach and places which are off the grid, as a source of standalone power for small-scale devices and tools to large infrastructures, as the primary power source for satellites, a era which began in late 1950s, in building related needs, for military purposes and usage in transportation as well.

II. AIM

Our main objectives in this experiment are:

1. Study of I-V Characteristic of a solar cell illuminated by an incandescent lamp, at different frequencies,
2. Study of I-V Characteristic of a solar cell illuminated by sun, at different frequencies,
3. Study how the junction capacitance varies with applied reverse bias and to estimate the doping density as well as the built-in potential by analysing the C-V characteristic of a solar cell.

III. APPARATUS

The apparatus needed for this experiment is:

1. Solar cell/panel,
2. Halogen lamp source as artificial light,
3. Optical bench to position the solar panel and a clamp,
4. Multimeters,
5. Filter papers of various colors,
6. Operational amplifier 0742 (TL072),
7. Resistors and capacitors,
8. Function generator and DC power supply
9. Breadboard and
10. Connecting wires

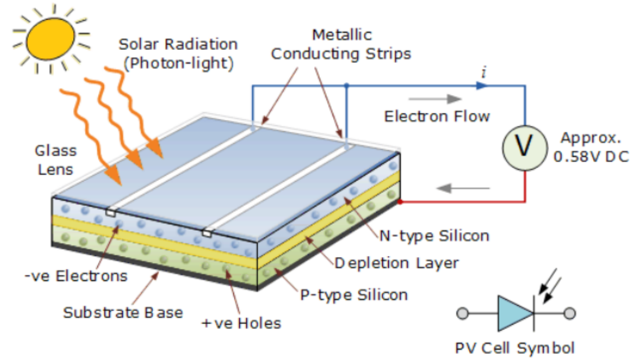


FIG. 2: Construction of a solar cell

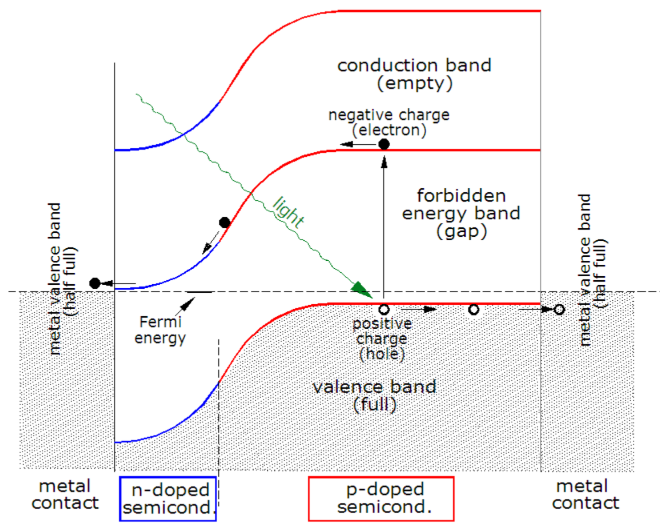


FIG. 3: Band diagram of a silicon solar cell, corresponding to very low current (horizontal Fermi level), very low voltage (metal valence bands at same height), and therefore very low illumination

IV. THEORY

Solar cell is the basic unit of solar energy generation system where electrical energy is extracted directly from light energy without any intermediate process. The working of a solar cell solely depends upon its photovoltaic effect, hence a solar cell also known as photovoltaic cell. A solar cell is basically a semiconductor p-n junction device. It is formed by joining p-type (high concentration of hole or deficiency of electron) and n-type (high concentration of electron) semiconductor material. at the junction excess electrons from n-type try to diffuse to p-side and vice-versa. Movement of electrons to the p-side exposes positive ion cores in n- side, while movement of holes to the n-side exposes negative ion cores in the p-side. This results in an electric field at the junction and forming the depletion region. When sunlight falls on the solar cell, photons with energy greater than band gap of the semiconductor are absorbed by the cell and generate electron-hole (e-h) pair. These e-h pairs migrate respectively to n- and p- side of the p0n junction due to electrostatic force of the field across the junction. In this way a potential difference is established between two sides of the cell. Typically a solar or photovoltaic cell has negative front contact and positive back contact. A semiconductor p-n junction is in the middle of these two contacts like a battery. If these two sides are connected by an external circuit, current will start flowing from positive to negative terminal of the solar cell. This is basic working principle of a solar cell. For silicon, the band gap at room temperature is $E_g = 1.1\,\text{eV}$ and the diffusion potential is $U_D = 0.5$ to $0.7\,\text{V}$. Construction of a Si solar cell is depicted in figure (2).

A. Solar cell parameters

Materials scientists often characterise solar cells in terms of simple circuit analysis; these typically include a p-n junction diode, a shunt resistance and a series resistor. Therefore, electrical characterization using a combination of DC and AC techniques allows the scientist to measure each of these components within the cell. Furthermore, different cell chemistries are at various stages of development and therefore some systems still require a significant effort in understanding the underlying physics of the devices. For example, polycrystalline Silicon is well understood as it has benefited from over 40 years R&D effort from the semiconductor industry. However, limitations due to cost and low theoretical efficiencies are driving scientists to seek new materials such as III-V compounds and polymeric systems in which the basic science is less mature. At present, scientists are engaged in a number of parallel strategies to improve the performance of next generation devices such as fundamental material characterization, multiple junction arrays and development of device structure. This necessitates the use of complex, accurate and flexible electrical characterization instruments that can meet the future demands of the scientists in this field.

Photovoltaic solar cells convert the suns radiant light directly into electricity. With increasing demand for a clean energy source and the sun's potential as a free energy source, has made solar energy conversion as part of a mixture of renewable energy sources increasingly important. As a result, the demand for efficient solar cells, which convert sunlight directly into electricity, is growing faster than ever before.

Photovoltaic (PV) cells are made made almost entirely from semiconductor silicon that has been processed into an extremely pure crystalline material which absorbs the photons from sunlight.

The photons hit the sillicon atoms releasing electrons causing an electric current to flow when the photoconductive cell is connected to an external load. For example, a battery. There are a variety of different measurements we can make to determine the solar cell's performance, such as its power output and its conversion efficiency.

B. I-V characteristics of a solar cell

The Solar Cell I-V Characteristic Curves shows the current and voltage (I-V) characteristics of a particular photovoltaic (PV) cell, module or array. It gives a detailed description of its solar energy conversion ability and efficiency. Knowing the electrical I-V characteristics (more importantly P_{max}) of a solar cell, or panel is critical in determining the device's output performance and solar efficiency.

According to Lindholm *et al.*, the I-V curve of a solar cell is the superposition of the I-V curve of the solar cell diode in the dark with the light-generated current. An understanding of the performance of a solar cell device can be gleaned with the I-V characterization technique. The voltage is ramped linearly or in staircase mode from the open circuit value (V_{OC}) to the Short Circuit Voltage (V_{SC}) and the generated current is measured. Depending upon the parameter of interest, the I-V characteristics are either performed under illumination at different light intensities or in the dark.

This simple result contains a large amount of useful information and the following parameters can be extracted from this data including I_{SC} or the short-circuit current, J_{SC} or the short-circuit current density, V_{OC} or the open circuit Voltage, P_{max} or the maximum power point. I_{max} or the current at P_{max}, V_{max} or the voltage at P_{max}, FF or the fill factor and η or the conversion efficiency.

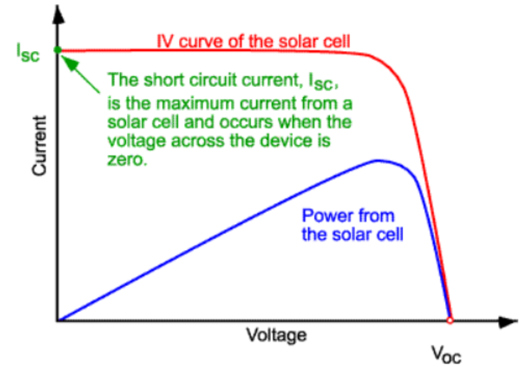


FIG. 4: I-V curve of a solar cell showing the short-circuit current.

1. The Short-circuit current

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). Usually written as ISC, the short-circuit current is shown in figure (4). The short-circuit current is due to the generation and collection of light-generated carriers. For an ideal solar cell at most moderate resistive loss mechanisms, the short-circuit current and the light-generated current are identical. Therefore, the short-circuit current is the largest current which may be drawn from the solar cell.

The short-circuit current depends on a number of factors like the area of the solar cell, the number of photons or the power of the incident light source, the spectrum of the incident light, the optical properties (absorption and reflection) of the solar cell and the minority-carrier collection probability of the solar cell, which depends chiefly on the surface passivation and the minority carrier lifetime in the base.

2. The Open-circuit Voltage

The open-circuit voltage, V_{OC}, is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current. The open-circuit voltage is shown in figure (5).

3. Fill factor

The short-circuit current and the open-circuit voltage are the maximum current and voltage respectively from a solar cell. However, at both of these operating points, the power

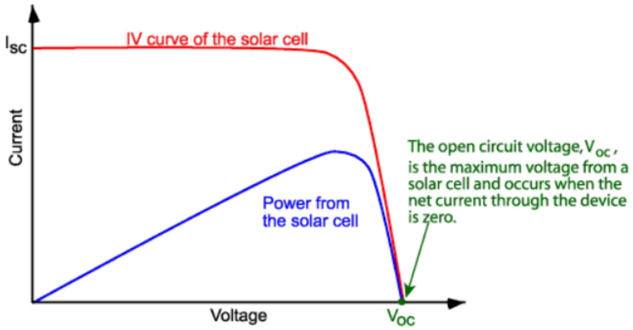


FIG. 5: I-V curve of a solar cell showing the open-circuit voltage.

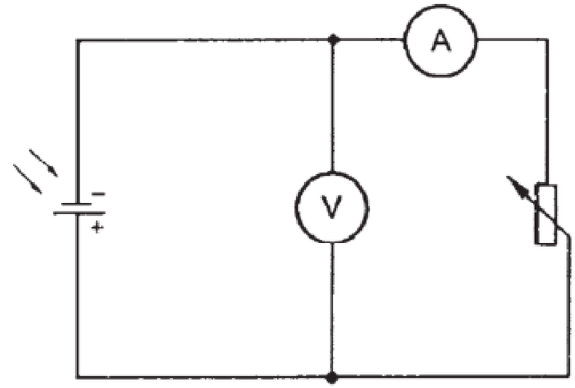


FIG. 6: Caption

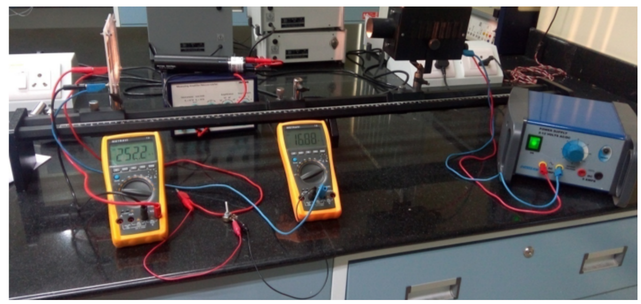


FIG. 7: Experimental set-up for I-V characterization of solar cell illuminated by lamp.

from the solar cell is zero. The "fill factor", more commonly known by its abbreviation "FF", is a parameter which, in conjunction with Voc and Isc, determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of Voc and Isc so that:

$$FF = \frac{P_{max}}{V_{OC} \times I_{SC}} \tag{1}$$

Graphically, the FF is a measure of the "squareness" of the solar cell and is also the area of the largest rectangle which will fit in the IV curve.

4. The Shockley Diode Equation

The Shockley diode equation or the diode law, named after transistor co-inventor William Shockley of Bell Telephone Laboratories, gives the I–V (current-voltage) characteristic of an idealized diode in either forward or reverse bias (applied voltage). Illuminating the cell adds to the normal dark currents in the diode so that the diode law becomes:

$$I = I_0\left[\exp\left(\frac{qv}{nkT}\right) - 1\right] - I_L \tag{2}$$

where I_0 is the dark saturation current or the diode leakage current in absence of light, q is the electric charge, V is the applied voltage across the diode terminals, n is the ideality factor, k is the Boltzmann's constant, T is the temperature and I_L is the light generated current.

5. Experimental set-up

A typical circuit for measuring I-V characteristics is shown in figure (6).

6. Efficiency

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell.

C. C-V characteristics of a solar cell

Capacitance voltage measurements can be used to characterise fundamental properties of solar cells including an estimate of the charge carrier density and the drive level capaci-

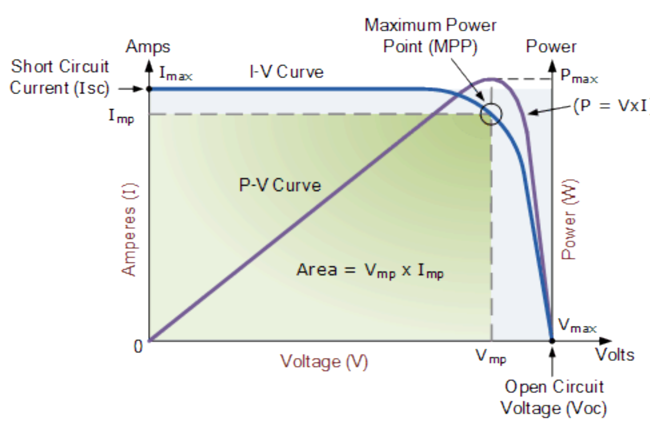


FIG. 8: A typical I-V curve and power curve for a solar cell.

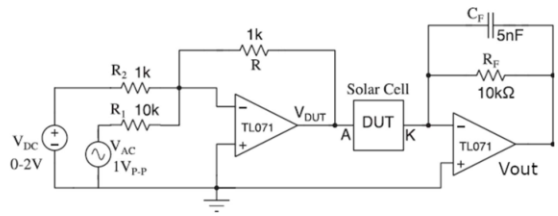


FIG. 9: Circuit to measure CV data

tance profile.

When a p-n junction is reverse biased, uncompensated acceptor ions in the p- side of the junction and an equal number of ionized donors on the n- side of junction form the space charge region. Since there are no mobile carriers in this region, only the free carriers at the edge of the depletion region can respond to the externally applied ac field. The junction thus resembles a parallel plate capacitor, whose capacitance is specified as

$$C = \left|\frac{dQ}{dV_{DC}}\right| = \frac{\varepsilon_0 \varepsilon_s A}{x_d} \tag{3}$$

where Q is the charge (free charge carriers) on either side of the junction, V_{DC} is the applied voltage, ε_s is the dielectric constant of the semiconductor, ε_0 is the permittivity of free space, and A is the area of the p-n junction. The depletion region width, x_d, for a reverse biased junction with constant doping density N_d is given by

$$x_d = \sqrt{\frac{2\varepsilon_0 \varepsilon_s (V_{bi} + V_{DC})}{qN_d}} \tag{4}$$

V_{bi} is the built-in voltage, q is the charge on an electron (1.6×10^{-19} C) and N_d is the doping density. From equations (3) and (4), it follows that

$$\frac{1}{C^2} = \left(\frac{x_d}{\varepsilon_0 \varepsilon_s A}\right)^2 = \frac{2(V_{bi} + V_{DC})}{q\varepsilon_0 \varepsilon_s A^2 N_d} \tag{5}$$

A plot of $1/C^2$ versus V_{DC} is a straight line with slope $d(1/C^2)/dV = 2/(q\varepsilon_0\varepsilon_s A^2 N_d)$. By obtaining this plot, one can easily find doping density N_d from the slope. The built-in potential V_{bi} could be estimated from either the Y-axis intercept $(2V_{bi}/(q\varepsilon_0\varepsilon_s A^2 N_d))$.

1. Mechanism

The circuit diagram for C-V characterizations of the solar cell is given in figure (9).

The capacitance of the solar cell (Device under test, DUT) depends strongly on the applied DC voltage. Since the experiment involves measurement of the C-V profile of the capacitor, the circuit must also be designed to apply an additional DC voltage across the capacitor (solar cell) that can be varied, while measuring the AC current to extract the capacitance. In our setup, we apply a variable DC bias and a small AC signal (small enough not to perturb DC bias and not affect the charge polarization due to the DC bias) to the DUT (Device Under Test). This is accomplished by using a basic 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 which is then connected to the DUT. The voltage V_{DUT} in figure (9) is thus given by the following equation

$$V_{DUT} = -R\left(\frac{V_{DC}}{R_2} + \frac{V_{AC}}{R_1}\right) \tag{6}$$

The AC voltage amplitude across the DUT (solar cell) is thus one tenth of the applied input DC voltage (smaller AC voltage can also be applied but we are limited by the sensitivity of our measuring instrument). One end (Anode, A) of the solar cell is connected to the output of the summing circuit while the other end (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 transimpedance amplifier (I to V converter) so that the current flowing through the capacitor is converted into voltage, a multimeter. The transimpedance amplifier generates a voltage output that is proportional to the DUT capacitance (C_{DUT}) and V_{DUT}. The magnitude of this voltage is given by following equation

$$V_{OUT} = V_{DUT}\frac{C_{DUT}}{C_F}\frac{1}{\sqrt{1 + \frac{1}{(\omega R_F C_F)^2}}} \tag{7}$$

D. Integrators and Differentiators

The electronic circuits which perform the mathematical operations such as differentiation and integration are called as differentiator and integrator, respectively. A differentiator is an electronic circuit that produces an output equal to the first derivative of its input.

An op-amp based differentiator produces an output, which is equal to the differential of input voltage that is applied to its inverting terminal. The circuit diagram of an op-amp based differentiator is shown in figure (10). In the above circuit, the non-inverting input terminal of the op-amp is connected to ground. That means zero volts is applied to its non-inverting input terminal.

According to the virtual short concept, the voltage at the inverting input terminal of opamp will be equal to the voltage present at its non-inverting input terminal. So, the voltage at the inverting input terminal of op-amp will be zero volts.

The nodal equation at the inverting input terminal's node is

$$\begin{aligned} C\frac{d(0-V_i)}{dt} + \frac{0-V_0}{R} &= 0 \\ \implies -C\frac{dV_i}{dt} &= \frac{V_0}{R} \\ \implies V_0 &= -RC\frac{dV_i}{dt} \end{aligned} \tag{8}$$

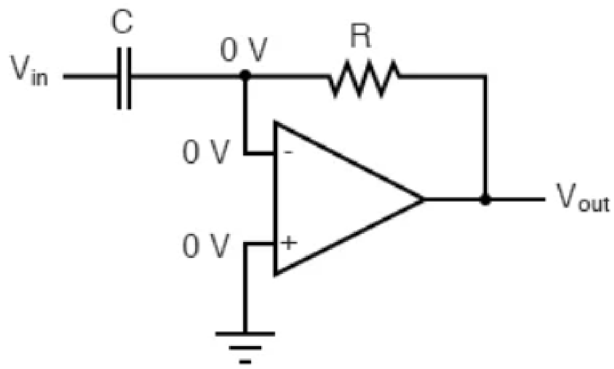


FIG. 10: Circuit diagram of a differentiator circuit

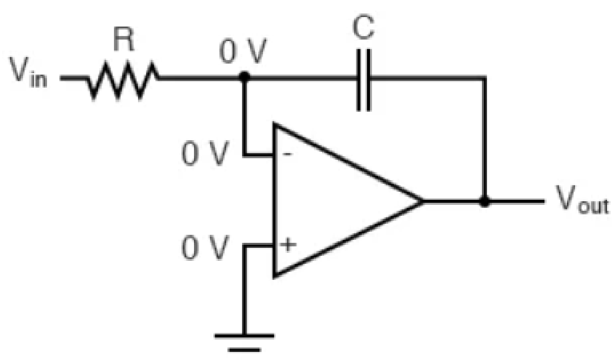


FIG. 11: Circuit diagram of a differentiator circuit

Thus, the op-amp based differentiator circuit shown above will produce an output, which is the differential of input voltage V_i, when the magnitudes of impedances of resistor and capacitor are reciprocal to each other.

An integrator is an electronic circuit that produces an output that is the integration of the applied input. An op-amp based integrator produces an output, which is an integral of the input voltage applied to its inverting terminal. The circuit diagram of an op-amp based integrator is shown in figure (11). In the circuit shown above, the non-inverting input terminal of the op-amp is connected to ground. That means zero volts is applied to its non-inverting input terminal.

According to virtual short concept, the voltage at the inverting input terminal of op-amp will be equal to the voltage present at its non-inverting input terminal. So, the voltage at the inverting input terminal of op-amp will be zero volts. The nodal equation at the inverting input terminal is

$$\begin{aligned} \frac{0-V_i}{R} + C\frac{d(0-V_0)}{dt} &= 0 \\ \implies -\frac{V_i}{R} &= C\frac{V_0}{dt} \\ \implies \int dv_0 &= \int \left(-\frac{V_i}{RC}\right) \\ \implies V_0 &= -\frac{1}{RC}\int V_t dt \end{aligned} \tag{9}$$

So, the op-amp based integrator circuit discussed above will produce an output, which is the integral of input voltage V_i, when the magnitude of impedances of resistor and capacitor are reciprocal to each other.

V. OBSERVATIONS

The following preliminary observations were made

1. For the I-V characterization, the supply voltage to the incandescent halogen lamp was 6 V.
2. The distance between lamp and solar cell was kept around 5 cm.
3. The frequency of the function generator for C-V characterization was set to be at 2 kHz.
4. The circuit components (resistors, capacitors) of C-V characterization are marked in the figure (9).
5. Electronic charge on the electron is $q = 1.6 \times 10^{-19}$ C and permittivity of free space is $\varepsilon_0 = 8.85 \times 10^{-12}\,\mathrm{m^{-3}\,kg^{-1}\,s^4\,A^2}$.
6. The dielectric constant for Si (solar cell) is $\varepsilon_s = 11.7$.
7. The area of the p-n junction is $A = 61.75\,\mathrm{cm}^2$.

The data for I-V characterization of the solar cell illuminated by the incandescent halogen lamp is tabulated in table (I). The data for I-V characterization of the solar cell illuminated by the sun is tabulated in table (II). The I-V curves for illumination by the incandescent halogen lamp against various filters are plotted in figure (12) and for illumination by the sun in figure (13). The parameters so obtained from the I-V characteristic curves are tabulated in tables (V) and (VI).

The data for C-V characterization of the solar cell in light conditions is tabulated in table (III) and in dark conditions in table (IV). The corresponding plots of C versus V_{DC} and $1/C^2$ versus V_{DC} are plotted in figures (14) and (15).

VI. CALCULATIONS

A. Efficiency of the solar cell under illumination by the Sun

Efficiency is defined as

$$\eta = \frac{\text{Power output}}{\text{Power input}} \tag{10}$$

TABLE I: I-V characterization of the solar cell illuminated by an incandescent halogen lamp with various filters

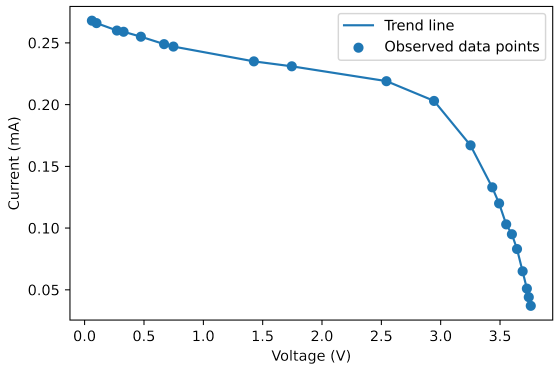
No Filter		**Red filter**		**Green filter**		**Yellow filter**		**Pink filter**	
Voltage (V)	*Current* (mA)	*Voltage* (V)	*Current* (mA)	*Voltage* (V)	*Current* (mA)	*Voltage* (V)	*Current* (mA)	*Voltage* (V)	*Current* (mA)
3.759	0.037	3.73	0.037	3.7	0.067	3.77	0.038	3.93	0.039
3.742	0.044	3.7	0.052	3.68	0.076	3.73	0.058	3.84	0.058
3.726	0.051	3.68	0.064	3.65	0.09			3.81	0.074
3.69	0.065	3.64	0.079	3.563	0.118	3.7	0.075	3.77	0.094
3.643	0.083			3.545	0.127			3.74	0.112
3.6	0.095	3.578	0.1	3.476	0.148	3.635	0.1	3.69	0.134
3.552	0.103							3.643	0.154
3.492	0.12	3.501	0.125	3.395	0.168	3.589	0.118	3.572	0.179
3.434	0.133							3.478	0.205
3.251	0.167	3.424	0.145	3.311	0.185	3.523	0.138	3.371	0.226
								3.176	0.249
2.944	0.203	3.268	0.177	3.182	0.203	3.386	0.17	2.739	0.267
								2.262	0.277
2.543	0.219	3.123	0.196	3.017	0.214	3.248	0.192	1.636	0.289
1.745	0.231							1.365	0.297
1.426	0.235	2.555	0.221	2.348	0.233	2.833	0.218	1.257	0.303
0.748	0.247							1.07	0.309
0.669	0.249	0.906	0.254	1.78	0.243	0.888	0.246	0.723	0.32
0.474	0.255			1.078	0.257			0.284	0.337
0.328	0.259	0.245	0.262	0.65	0.268	0.085	0.257	0.265	0.343
0.272	0.26			0.273	0.279			0.133	0.35
0.1	0.266	0.076	0.266	0.098	0.282	0.068	0.26	0.089	0.353
0.061	0.268	0.059	0.268	0.059	0.285	0.054	0.263	0.064	0.356

TABLE II: I-V characterization of the solar cell illuminated by the sun with various filters

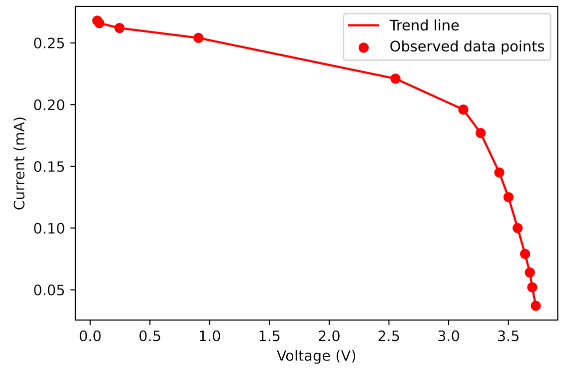
No Filter		**Red filter**		**Yellow filter**		**Pink filter**	
Voltage (V)	*Current* (mA)	*Voltage* (V)	*Current* (mA)	*Voltage* (V)	*Current* (mA)	*Voltage* (V)	*Current* (mA)
6	0.05	5.67	0.05	5.73	0.06	5.78	0.06
5.96	0.41	5.67	1.77	5.71	0.12	5.76	0.35
5.92	0.98	5.6	7.76	5.71	0.26	5.73	2.74
5.91	1.1	5.56	10.32	5.7	0.86	5.67	7.33
5.9	2.17	5.4	21.26	5.61	8.83	5.64	9.82
5.88	3.44	5.33	25.8	5.49	18.64	5.59	13.78
				5.43	22.63	5.48	21.62
5.78	11.98	5.26	29.06	5.26	32.33	5.35	29.86
				5.18	36.69		
5.68	21.26	5.2	32.2	5.08	41.1	5.26	35.45
				4.94	44.9	5.16	40.1
5.54	31.55	5.1	36.26	4.78	46.5	4.98	46.1
5.47	38.6	4.98	40.1	3.7	47.4	4.29	49.4
5.25	52.8	4.83	42.7	3	47.5	3.23	49.4
5.1	61.5	4.13	43	2.12	48.4	1.855	50.9
1.17	69.8	0.522	45.6	1.69	48.9	0.598	52.5
1.1	70.1	0.452	45.9	0.28	51.1	0.454	52.9

We can find the incident or power input using average solar irradiance which is $100\,\mathrm{mW\,m^{-2}}$. The area of the solar cell is $16\,\mathrm{cm^2}$. Therefore, power input is $1600\,\mathrm{mW}$. The power output in absence of any filter when the solar cell was illuminated by the Sun was $313.65\,\mathrm{mW}$ as given in table (VI). From here

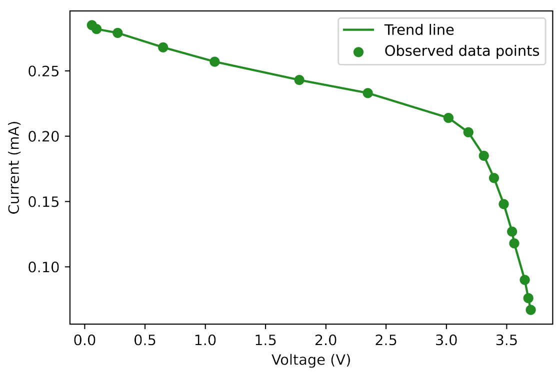
$$\boxed{\eta = \frac{313.65}{1600} = 19.6\%} \tag{11}$$



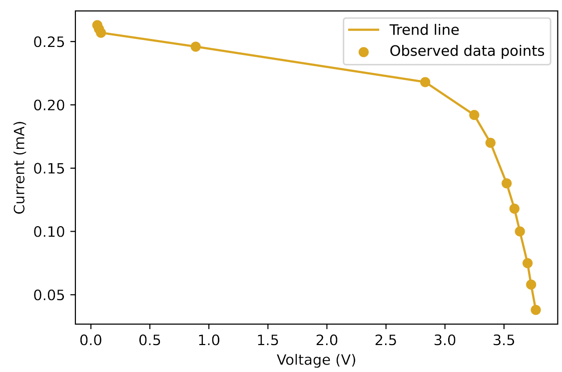
(a) With no filter



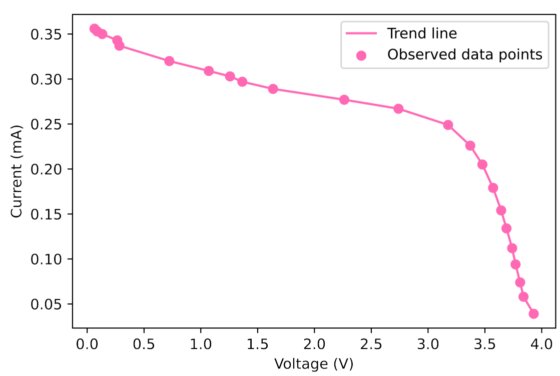
(b) With red filter



(c) With green filter



(d) With yellow filter



(e) With pink filter

FIG. 12: I-V characteristic curve of solar cell illuminated by the incandescent halogen lamp with various filters

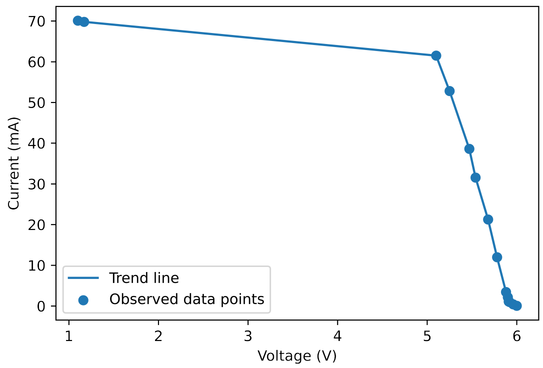
B. Doping density and built-in voltage of the solar cell under light conditions

Using linear regression analysis, the equation of the straight line obtained by fitting the $1/C^2$ versus V_{DC} data points in light conditions (figure (14)) is $y = 252.06475729323213x - 108.26658750148931$. The unit of slope is $\mu F^{-2}\,V^{-1}$. Therefore, $m = 2.52 \times 10^{14}\,F^{-2}\,V^{-1}$. Similarly, Y-intercept is $-1.08 \times 10^{-4}\,F^{-2}$.

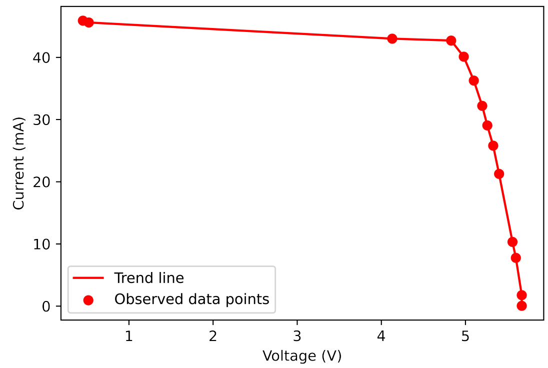
Now the doping density is given by

$$N_d = \frac{2}{q\varepsilon_0\varepsilon_s A^2 m} \tag{12}$$

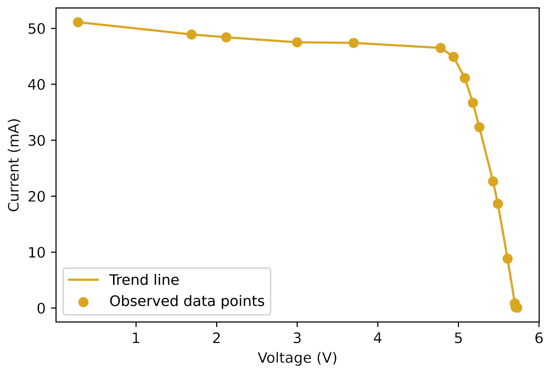
where m is the slope. Putting in the values, we get $N_d = 1.25 \times 10^{19}\,m^{-3}$.



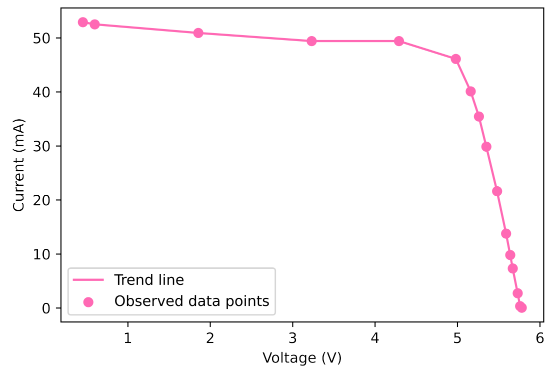
(a) With no filter



(b) With red filter



(c) With yellow filter



(d) With pink filter

FIG. 13: I-V characteristic curve of solar cell illuminated by the sun with various filters

TABLE III: C-V characterization of the solar cell under light conditions

V_{DC} (V)	V_{DUT} (V)	V_{OUT} (V)	C_{DUT} (μF)	$1/C^2$ (μF^{-2})
0.3	-0.336	9.73	0.272	5.000
0.4	-0.397	9.78	0.231	18.721
0.5	-0.543	9.83	0.170	34.668
0.6	-0.657	9.82	0.140	50.855
0.7	-0.783	9.91	0.119	70.926
0.8	-0.822	9.9	0.113	78.326
0.9	-0.936	10.01	0.100	99.338
1	-1.004	9.98	0.093	114.984
1.1	-1.069	10	0.088	129.833
1.2	-1.218	10.03	0.077	167.542
1.3	-1.32	10.03	0.071	196.778
1.4	-1.399	10.04	0.067	220.596
1.5	-1.494	10.07	0.063	250.076
1.6	-1.598	10.06	0.059	286.674
1.7	-1.69	10.08	0.056	319.361
1.8	-1.81	10.06	0.052	367.783
1.9	-1.903	10.06	0.050	406.548
2	-1.993	10.1	0.048	442.386

TABLE IV: C-V characterization of the solar cell under dark conditions

V_{DC} (V)	V_{DUT} (V)	V_{OUT} (V)	C_{DUT} (nF)	$1/C^2$ (nF^{-2})
0.3	-0.346	0.019	0.515	3.768
0.4	-0.485	0.024	0.464	4.640
0.5	-0.564	0.027	0.449	4.957
0.6	-0.666	0.032	0.451	4.921
0.7	-0.762	0.036	0.443	5.090
0.8	-0.843	0.039	0.434	5.308
0.9	-0.943	0.044	0.438	5.219
1	-1.055	0.045	0.400	6.245
1.1	-1.15	0.045	0.367	7.420
1.2	-1.264	0.046	0.341	8.578
1.3	-1.345	0.048	0.335	8.921
1.4	-1.453	0.049	0.316	9.990
1.5	-1.565	0.049	0.294	11.590
1.6	-1.629	0.049	0.282	12.557
1.7	-1.756	0.05	0.267	14.013
1.8	-1.843	0.051	0.260	14.837
1.9	-1.976	0.051	0.242	17.055
2	-2.05	0.052	0.238	17.658

TABLE V: Parameters of solar cell under illumination by the incandescent halogen lamp determined from the I-V characteristic curve

Filter	$\mathbf{V_{OC}}$ (V)	$\mathbf{I_{SC}}$ (mA)	**Power**, P (mW)	$\mathbf{V_{max}}$ (V)	$\mathbf{I_{max}}$ (mA)	$\mathbf{P_{max}}$ (mW)	**Fill factor, FF**	**Average fill factor**
No filter	3.759	0.268	1.007	2.944	0.203	0.598	59.323 %	
Red filter	3.73	0.268	1	3.123	0.196	0.612	61.233 %	
Green filter	3.7	0.285	1.055	3.182	0.203	0.646	61.256 %	60.247 %
Yellow filter	3.77	0.263	0.992	3.248	0.192	0.624	62.896 %	
Pink filter	3.93	0.356	1.399	3.176	0.249	0.791	56.525 %	

TABLE VI: Parameters of solar cell under illumination by the sun determined from the I-V characteristic curve

Filter	$\mathbf{V_{OC}}$ (V)	$\mathbf{I_{SC}}$ (mA)	**Power**, P (mW)	$\mathbf{V_{max}}$ (V)	$\mathbf{I_{max}}$ (mA)	$\mathbf{P_{max}}$ (mW)	**Fill factor, FF**	**Average fill factor**
No filter	6	70.1	420.6	5.1	61.5	313.65	74.572 %	
Red filter	5.67	45.9	260.253	4.83	42.7	206.241	79.246 %	76.203 %
Yellow filter	5.73	51.1	292.803	4.78	46.5	222.27	75.911 %	
Pink filter	5.78	52.9	305.762	4.98	46.1	229.578	75.084 %	

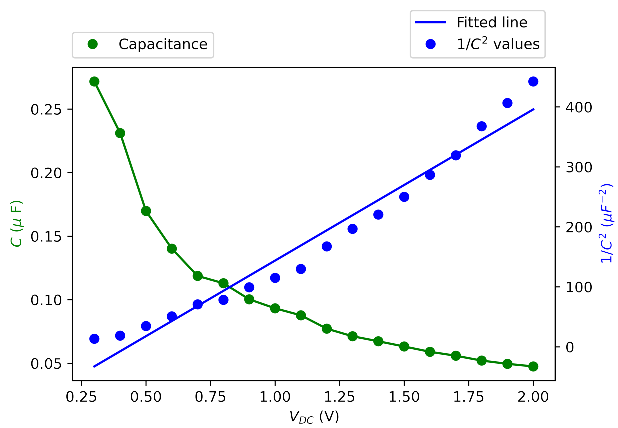


FIG. 14: C-V characteristic curve for the solar cell under light conditions

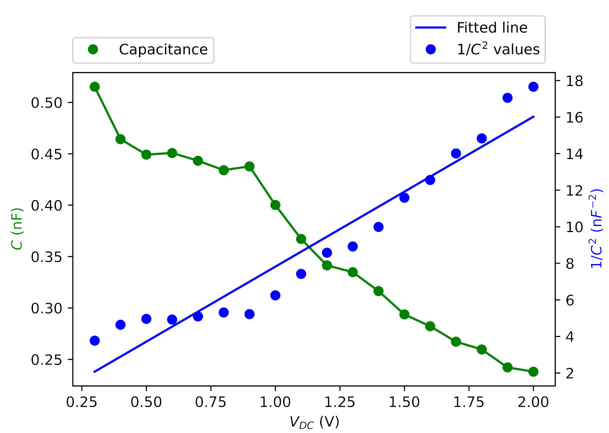


FIG. 15: C-V characteristic curve for the solar cell under dark conditions

Similarly, the built-in voltage, V_{bi}, is given by

$$V_{bi} = \frac{c}{m} \tag{13}$$

where c is the Y-intercept and m is the slope. Putting in the values, we get $V_{bi} = 0.43\,\mathrm{V}$.

C. Doping density and built-in voltage of the solar cell under dark conditions

Using linear regression analysis, the equation of the straight line obtained by fitting the $1/C^2$ versus V_{DC} data points in dark conditions (figure (15)) is $y = 8.204535788895768x - 0.3926397132301327$. The unit of slope is $\mu\mathrm{F}^{-2}\,\mathrm{V}^{-1}$. Therefore, $m = 8.20 \times 10^{18}\,\mathrm{F}^{-2}\,\mathrm{V}^{-1}$. Similarly, Y-intercept is $-3.93 \times 10^{-10}\,\mathrm{F}^{-2}$.

Now the doping density is given by

$$N_d = \frac{2}{q\varepsilon_0\varepsilon_s A^2 m} \tag{14}$$

where m is the slope. Putting in the values, we get $N_d = 3.86 \times 10^{14}\,\mathrm{m}^{-3}$.

Similarly, the built-in voltage, V_{bi}, is given by

$$V_{bi} = \frac{c}{m} \tag{15}$$

where c is the Y-intercept and m is the slope. Putting in the values, we get $V_{bi} = 0.048\,\mathrm{V}$.

VII. ERROR ANALYSIS

A. In Doping density and built-in voltage of the solar cell under light conditions

Error in doping density N_d is given by

$$\delta N_d = \frac{\delta m}{m} \times N_d \tag{16}$$

Using NumPy library's regression analysis, the error in slope was obtained as $\delta m = 1.26 \times 10^{13}\,\mathrm{F}^{-2}\,\mathrm{V}^{-1}$. Putting in the values we get $\delta N_d = 0.05 \times 10^{19}\,\mathrm{m}^{-3}$.

Similarly, error in built-in voltage, V_{bi}, is given by

$$\delta V_{bi} = V_{bi}\sqrt{\left(\frac{\delta y}{y}\right)^2 + \left(\frac{\delta m}{m}\right)^2} \tag{17}$$

Here, δy is the error in Y-intercept and using NumPy library's regression analysis it was found to be $\delta y = -1.59 \times 10^{-5}\,\mathrm{F}^{-2}$. Putting in the values, we get $\delta V_{bi} = 0.07\,\mathrm{V}$.

B. In Doping density and built-in voltage of the solar cell under dark conditions

Error in doping density N_d is given by

$$\delta N_d = \frac{\delta m}{m} \times N_d \tag{18}$$

Using NumPy library's regression analysis, the error in slope was obtained as $\delta m = 0.58 \times 10^{18}\,\mathrm{F}^{-2}\,\mathrm{V}^{-1}$. Putting in the values we get $\delta N_d = 2.72 \times 10^{13}\,\mathrm{m}^{-3}$.

Similarly, error in built-in voltage, V_{bi}, is given by

$$\delta V_{bi} = V_{bi}\sqrt{\left(\frac{\delta y}{y}\right)^2 + \left(\frac{\delta m}{m}\right)^2} \tag{19}$$

Here, δy is the error in Y-intercept and using NumPy library's regression analysis it was found to be $\delta y = 0.73 \times 10^{-9}\,\mathrm{F}^{-2}$. Putting in the values, we get $\delta V_{bi} = 0.009\,\mathrm{V}$.

VIII. RESULTS

1. The average fill factor for the solar cell under Incandescent lamp was found to be 60.247 %.
2. The average fill factor for the solar cell under sun was found to be 76.203 %.
3. The power obtained under sun was much greater than lamp, as the intensity of sun is much higher.
4. The efficiency of the solar cell under illumination by the Sun was found to be $\eta = 19.6\%$.
5. The doping density in the solar cell under light conditions was found to be $N_d = (1.25 \pm 0.05) \times 10^{19}\,\mathrm{m}^{-3}$.
6. The doping density in the solar cell under dark conditions was found to be $N_d = (3.86 \pm 0.27) \times 10^{14}\,\mathrm{m}^{-3}$.
7. The built-in voltage of the solar cell in light conditions was found to be $V_{bi} = (0.43 \pm 0.07)\,\mathrm{V}$.
8. The built-in voltage of the solar cell in light conditions was found to be $V_{bi} = (0.048 \pm 0.009)\,\mathrm{V}$.

IX. DISCUSSIONS

1. In the region (of I-V characteristics graph) where the I starts falling drastically, we can employ a potentiometer of larger resistance that can be better tuned to get more number of points in that region.
2. Under sun the current falls drastically, and readings must be taken carefully to obtain the maximum power.
3. I_{SC} was not constant with change in wavelength of light, even though it is dependent on intensity and not wavelength. This can be explained as there is a dependence of intensity on wavelength.
4. The photo diode in dark conditions works as normal p-n junction diode with applied reverse bias voltage.
5. The V_{OUT} of the solar cell in light condition was observed to be constant indicating that the maximum output voltage was achieved.
6. The transimpedance amplifier part of the circuit acts as an active low pass filter. The gain, V_{OUT}/V_{DUT} is high for low ω.
7. The decreasing trend of the C versus V_{DC} plots can be explained by the fact that as the applied voltage is reverse biased, the width of the depletion region increases with increase in the input V_{DC} which results in decreased capacitance.

X. PRECAUTIONS

1. Quite a few points are missed when there is a sudden variation in the current output because of small value of potentiometer used; this causes an error in determining the nature of graph.
2. The experiment done under the sun is subject to the weather conditions and causes error in readings as the weather fluctuates during the course of experiment.
3. Filter paper are another cause of error as the incident light on solar cell does not remain uniform instead plastic/glass filters should be used.
4. Do not disturb the setup while taking the measurements.
5. For dark conditions use a thick black cloth only.

6. Do not operate the diode in breakdown region.
7. This is a test.