Silicon (Si) Solar Cell

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1. Introduction

1.1 Motivation

In this experiment we have examined sample solar cells in order to get insight into different characteristics of solar cells. From the experimental data solar cells were characterized after the measurements. Effect of temperature and intensity are examined.

1.2 Solar Cell

Generation of electricity from sunlight is achieved by solar cell. Direct harvesting of the immense and never-ending power brought to us by the sun. Not long ago, this elegant way of generating electricity was associated with satellites and space stations, or remote off-grid locations needing electricity to power a light bulb in a cabin. Today, on the other hand, we can read that Germany generates 50% of its electric power from photovoltaic (PV) energy during mid-day hours on a sunny day [**1**]. In 2011, more than 28 GW of new PV generating capacity was installed globally [**2**]. This corresponds to about 200 km^2 of solar panels, or 1.5 times the size of the city of San Francisco! Obviously, our view on PV as a small niche market needs to be reviewed.

In a world where a rapidly increasing demand for energy is ever more strongly conflicting with an urgent need to cut back on greenhouse gas emissions, it seems to be necessary and inevitable that renewable energy sources will play a major role in the future global energy system. A recent report from the Intergovernmental Panel on Climate Change [3] predicts that wind and PV will account for up to 30% of the world's electricity production by 2050, even in the moderate scenarios.

Direct solar energy is a tremendous energy resource which delivers around 4x1024 J of energy to the surface of the earth per year (assuming a solar flux of 1 kW/m^2). The world's total energy consumption was around 5.6x1020 J [4] in 2010 which means that the solar energy hitting the earth in about one hour is sufficient to cover the energy-needs of the humanity for a whole year! This is by far the largest source of energy available to us, and a great candidate for a transition to a more sustainable energy system. Furthermore, silicon based PV is based on non-toxic, abundant materials, silicon being the second most abundant element in the earth's crust after oxygen.

PV is currently the fastest and rapidly growing renewable energy source, with an average growth rate of above 40% per year since the year 2000 (Figure 1.1). Silicon based solar cells have an 85% market share [5], and is thus the absolutely dominant technology in PV. The growth in PV has been linked to economic incentives, and continued growth in installed PV cannot rely on politically driven incentives alone. PV learning curves have shown a 20% reduction since 1970's in module prices per doubling of cumulative production [6], a quite tremendous price reduction. This trend in price reduction however, has to be continued as incentives are continuously being reduced. This can either happen through the reduction of production costs (fewer $ per solar cell), or by an increase in efficiency (more Watts per solar cell). A combination of both would of course be ideal. In the current scenario, the price for manufacturing of the solar cell and solar module has been dramatically reduced which leads to a situation where balance of system costs, such as installation costs, the costs of mounting brackets, land usage costs etc. are beginning to dominate the total cost of a PV energy system [7]. Increased efficiency of the solar cell will reduce the balance of the system costs for example by reducing the number of brackets and land area required for a given output power, implying that retaining or improving the efficiency of the solar cell is essential for the reduction of the PV system costs.

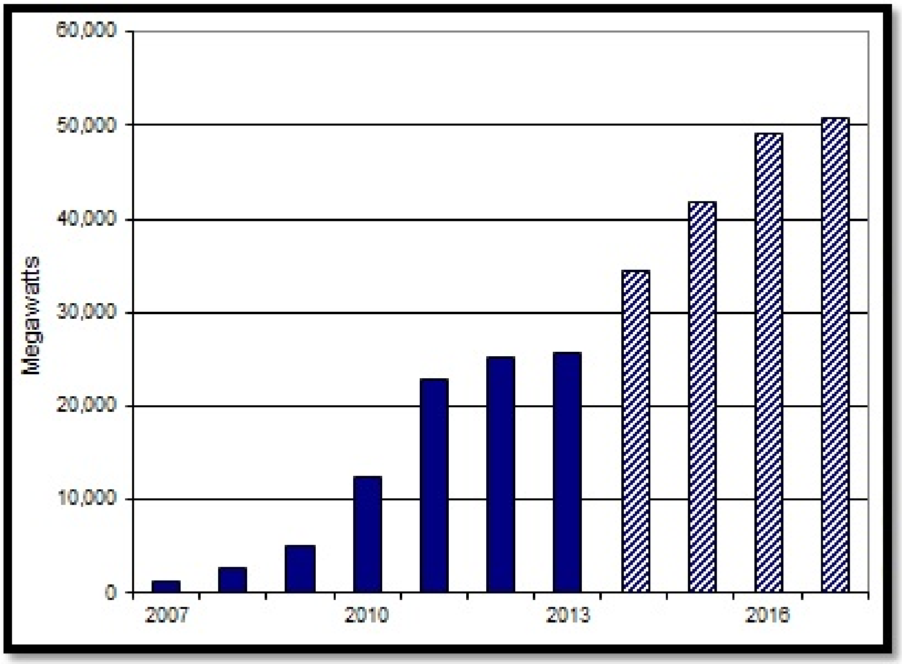


Figure 1.1: Total annual PV production. Data Source: [**13**]

1.3 Silicon Solar Cell

Solar cells operate by converting sunlight energy into electricity. In this section a brief review of the solar cell physics will be treated. For a more thorough introduction example [10] can be seen. One of the critical properties that make silicon suitable for the solar cell material is that, it is a semiconductor which possessing a band-gap. This band-gap is a range of energies that the electrons in the materials are not allowed to have. The electron can either have an energy placing it in its ground energy state in the valence band, or it can be in an excited state in the conduction band. The electron can transit from valence band to conduction band and back through excitation and recombination processes described below. The energy required for an excitation may come from a photon, being the smallest package of energy one can divide light into. The sunlight consists of photons with a wide range of energies. The energy of the photon corresponds to what we observe as the color of the light, where the blue light consists of photons with a higher energy, and the red light consists of photons with lower energy. The energy of the photon also corresponds to a wavelength of the light, where the blue light has a shorter wavelength, and the red light has a longer wavelength. The spectral energy distribution of the sunlight is shown in Figure 1.3 which adds up to 1000 W/m^2 at the surface of the earth under given conditions is known as the Air Mass 1.5 spectrum (AM1.5).

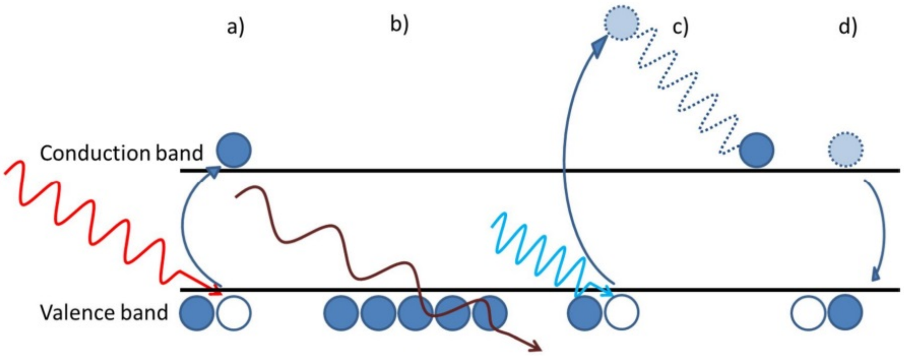


Figure 1.2: Illustration of some absorption and loss mechanisms in a solar cell. a) Absorption, b) photon with insufficient energy for absorption, c) absorption and thermalisation, d) recombination.

When a photon hits the silicon surface, it may be absorbed by an electron in the silicon, providing enough energy for the electron to be excited from its ground energy state in the valence band to an excited state in the conduction band, as indicated in Figure **??** (a). Such an absorption process may only take place if the photon carries an energy corresponding to at least the band gap energy. The electron being excited will leave behind a hole in the valence band, thus an electron-hole pair is created. In a solar cell, the electron-hole pair moves by diffusion until it reaches the p-n junction. The p-n junction is a built-in asymmetry in the solar cell, where an electric field ensures that the electron will travel in one direction, while the hole travels in the opposite direction. As such, the electron may reach one of the electrical contacts, while the hole reaches the other contact, as a result of a combination of random diffusion and directional drift in an electric field. This is the principal mechanism behind current generation in a solar cell. Only photons with high enough energy may be absorbed by the electrons. A photon with energy lower than the band-gap energy will not carry sufficient energy to lift the electron to the conduction band, and will as such not be absorbed in the semiconductor. Hence, its energy will not be converted into electricity.

This situation is indicated in Figure **??** (b), and is called the sub-bandgap loss. On the other hand, photons with high energy can create an electron-hole pair as indicated in Figure **??** (c), lifting the electron high above the conduction band edge. However, all the excess energy that is put into the electron will be rapidly lost, as the electron will collide with other electrons or atoms, losing energy until it reaches the conduction band edge. This loss process is called thermalisation.

1.4 Solar Cell Characteristics

1.4.1 Solar Cell Structure

A solar cell is an electronic device which directly converts the energy of the sunlight into electricity. Light shining on the solar cell produces both a current and a voltage to generate electric power. This process requires firstly, a material in which the absorption of light raises an electron to a higher energy state, and secondly, the movement of this higher energy electron from the solar cell into an external circuit. The electron then dissipates its energy in the external circuit and returns to the solar cell. A variety of materials and processes can potentially satisfy the requirements for the photovoltaic energy conversion, but in practice nearly all photovoltaic energy conversion uses semiconductor materials in the form of a p-n junction.

The basic steps in the operation of a solar cell are:
- the generation of light-generated carriers
- the collection of the light-generated carries to generate a current
- the generation of a large voltage across the solar cell and
- the dissipation of power in the load and in parasitic resistances.

1.4.2 Solar Cell Parameters

In this section few parameters of the solar cells will be explained. These parameters are the key factors which determine the performance of the solar cells. In order to understand solar cell performance, introduction to these parameters are highly recommended.

Current Voltage Characteristics I-V Curve

The IV curve of a solar cell is the superposition of the IV curve of the solar cell diode in the dark with the light-generated current. The light has the effect of shifting the IV curve down into the fourth quadrant where power can be extracted from the diode. Illuminating a cell adds to the normal "dark" currents in the diode so that the diode law becomes:

$$I = I_0[\exp\frac{qV}{nkT} - 1] - I_L \tag{1.1}$$

Where I_L = Light generated current; I_o = Saturation Current; q = electronic charge; V = Applied voltage; n = Ideality Factor (for Si = 2 and for Ge = 1); k = Boltzmann Constant

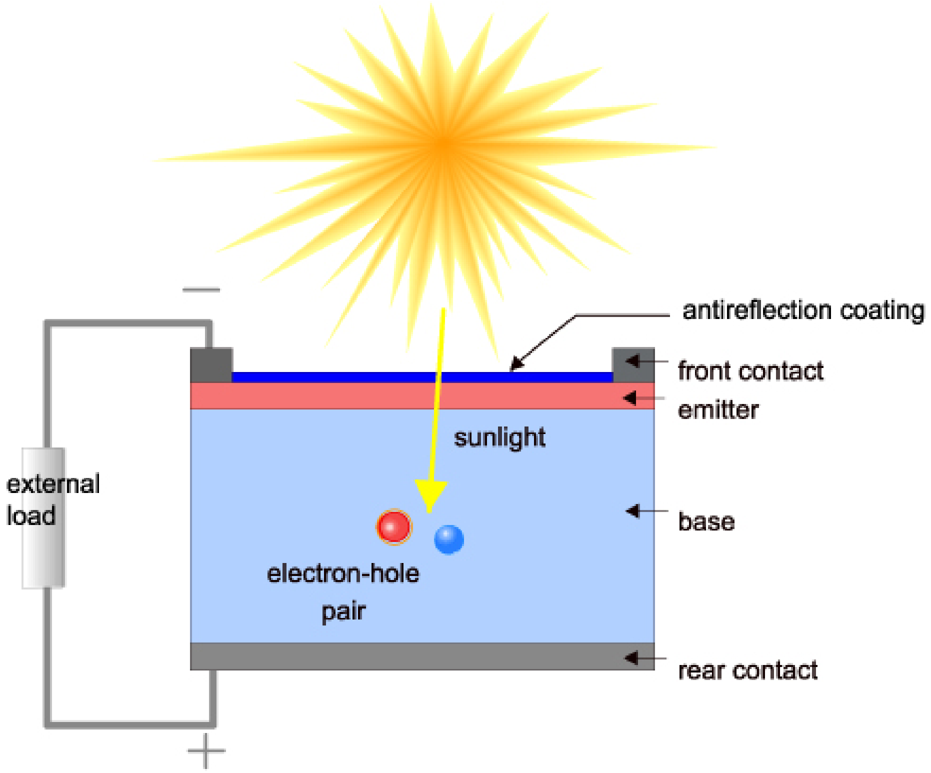


Figure 1.3: Cross Section of Solar Cell. [**11**]

1.4.3 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 on the IV curve Figure 1.4. 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.

1.4.4 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 on the IV curve (Figure 1.4).

1.4.5 Fill Factor FF

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 from the solar cell is

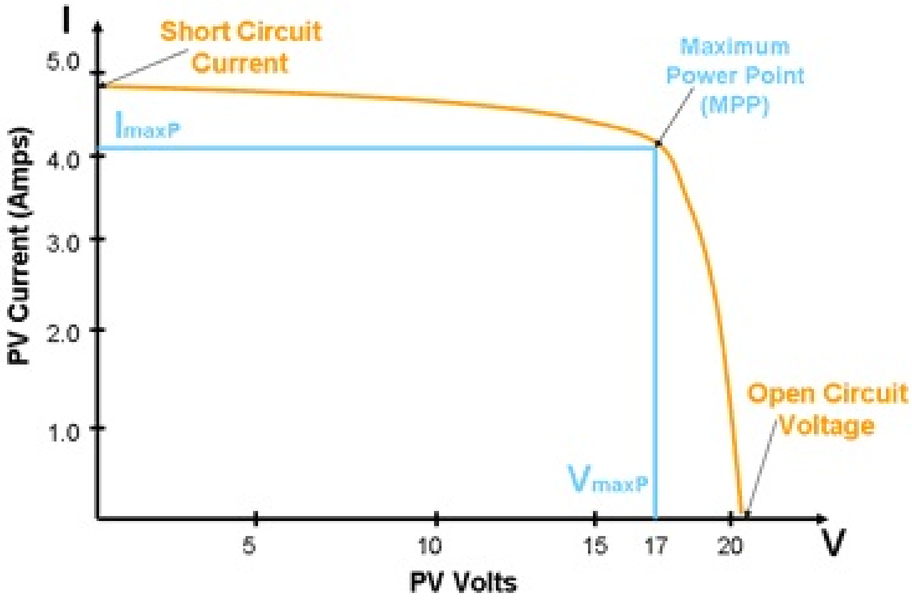


Figure 1.4: Current-Voltage I-V curve of a solar cell. [**11**]

zero. The "fill factor", more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V_{OC} and I_{sc}, 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 V_{OC} and I_{sc}. 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 (Figure 1.4).

$$FF = \frac{V_{oc} - ln(V_{oc} + 0.72)}{V_{oc} + 1} \tag{1.2}$$

Solar Cell Efficiency

The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

$$\eta = \frac{V_{OC} I_{sc} FF}{P_{in}} \tag{1.3}$$

where V_{OC} Open circuit voltage, I_{sc} short circuit current, FF fill factor and η efficiency.

2. Experiment

This experiment measurement was separated in three different parts. In the first exercise the intensity dependent IV characteristics of a silicon solar cell have been measured. In the second exercise, the band gap of silicon from short circuit current measurement have been spectrally resolved and in the final exercise, the temperature dependent characteristics of solar cell have been measured.

2.1 Measurement of intensity-dependent characteristics

Although three different types of solar cells in the laboratory have been expected, but only one has been received for others were out of order. However, only one sample of silicon solar cell has been used for the rest of the exercises. It was quite difficult to change the intensity of light linearly and hence, the distance between solar cell and light source is varied in order to change the intensity. From this measurement intensity dependent IV curve has been obtained.

At first, the current-voltage characteristics of the solar cell is measured for different distances between the halogen lamp and the given solar cell using LabView software. Different distances of 20, 30, 40 and 50cm between the light source and the solar-cell are taken and the experiment is carried for both p and n-side of the solar cell from -4 to 0.6 volt in steps of 60 increments.

2.2 Spectrally resolved short-circuit current measurements

The short-circuit current of the solar cell as a function of photon energy is measured and from that the band-gap of the silicon solar cell is determined. A spectrometer analysed the wavelength (400-1300 nm) emitting from the halogen lamp and the LabView software manipulated the data. There is also an amplifier present in order to amplify the current generated in the solar cell.

2.3 Measurement of temperature-dependent characteristics

Now the lamp is being switched off and the surface of the solar cell is being cooled down. The LabView software is noting the temperature (300-325 K) with the help of thermocouple and the temperature is being stabled down and then the current-voltage characteristics is recorded.

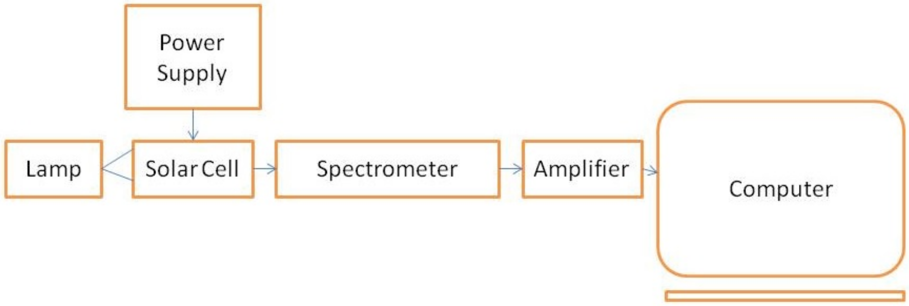


Figure 2.1: Schematic setup for the solar cell lab experiment.

3. Results and Analysis

3.1 Measurement of intensity-dependent characteristics

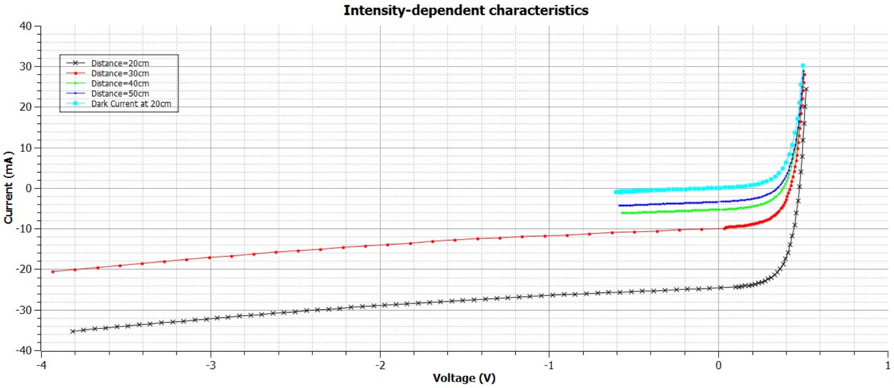
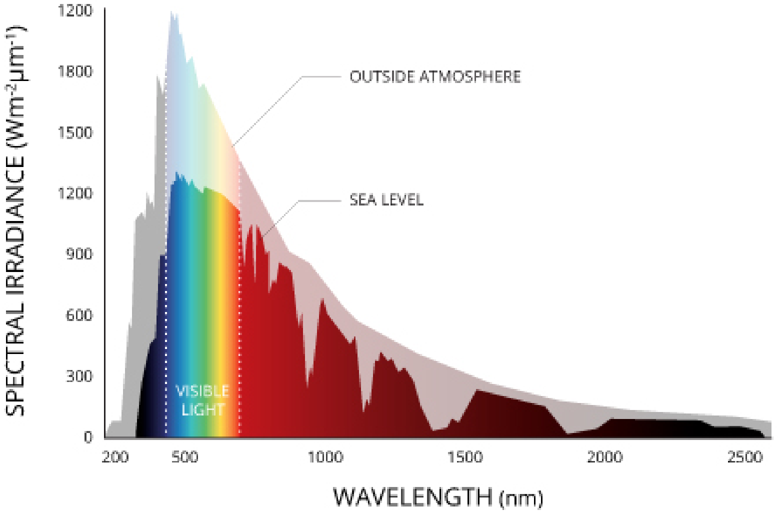
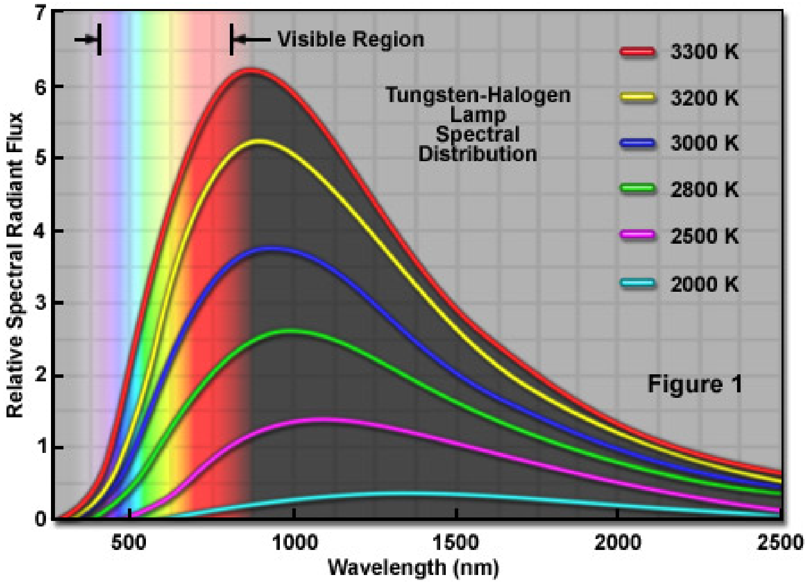


Figure 3.1: Intensity dependent current-voltage characteristics.

The current-voltage characteristics from -4V to 0.6V in steps of 0.01V as a function of intensity is plotted in 3.1. For the distance of 40cm and 50cm, data have been recorded from -0.6V instead of -4V and also for the case of dark current characteristic (illumination is switched off). For the dark current characteristic, current is very feeble and as soon as there is illumination, solar cell absorbs incoming photons and converts them to current electricity. With the increase in distance, current decreases which imply strong incident energy can excite more electrons to flow. Table 1 shows the manipulated data for different distances between the solar cell and the halogen lamp



(a) Solar spectral irradiance.



(b) Tungsten Lamp Spectrum.

Figure 3.2: Spectral Irradiance. [**12**]

Distance in cm	Open circuit voltage V_{OC} in V	Short circuit current I_{SC} in mA	Maximum Power P_{max} in mW	Fill Factor (FF)
20	0.479	-24.618	-7.120	0.600
30	0.421	-9.908	-2.258	0.540
40	0.380	-5.301	-1.001	0.497
50	0.350	-3.351	-0.510	0.435

Here fill factor FF of the given solar cell is calculated from the relation $FF = \frac{V_{max}I_{max}}{V_{oc}I_{sc}}$. The efficiency can be calculated from the relation given in equation 1.3 but incident power on the solar cell Pin has not been measured during the experiment. Figure 3.2a and figure 3.2b are the spectrum of solar radiation and halogen lamp respectively. From the diagrams it can be said that for lower wavelengths, i.e. for higher energies, the intensity of the irradiation of the sun is greater than that of the halogen lamp. Thus more photons will interact in the generation of electron-hole pairs thereby increasing the amount of current. So, the efficiency will be higher for sun than the halogen lamp. From equation 1.1 ideality factor can be determined.

3.2 Spectrally resolved short-circuit current measurements

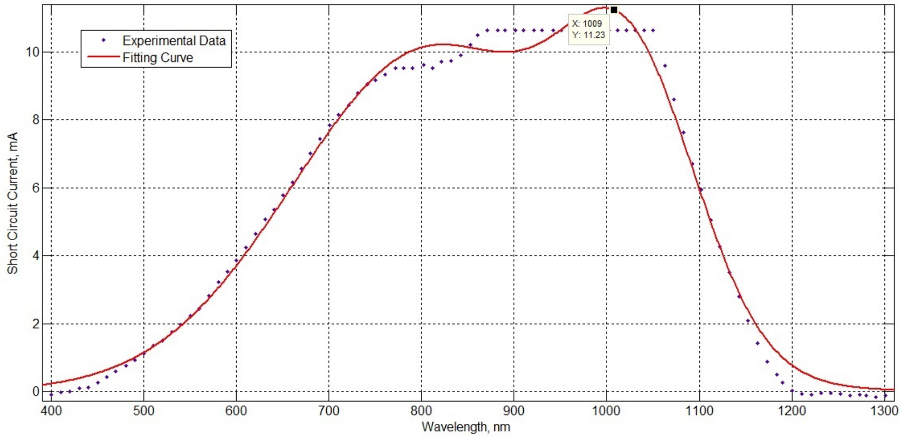


Figure 3.3: Spectrally resolved short circuit current.

From the figure 3.3 the band gap of the given silicon solar cell can be evaluated by using Planck-Einstein relationship between energy and frequency $E = h\nu$. Substituting $\nu = c/\lambda$, one obtain $E = hc/\lambda$, where h is the Planck's constant which is equals to $6.62X10^{-34}$ Js and c being the velocity of light in vacuum which is taken as $3X10^{8}$ m/s. From the graph, the absorption wavelength is selected to be 1009 nm and substituting this value one can achieve the band gap of the given silicon solar cell which came to be 1.2296 eV which is approximately equals the band gap of silicon in theory. From the theory of semiconductor it is known that for a narrow band gap one can get a broad spectrum to be absorbed

3.3 Measurement of temperature-dependent characteristics

The temperature dependent characteristic is shown in figure 3.4. From this characteristic, short circuit current, reverse blocking current and open circuit voltage as a function of temperature are plotted. After switching off the illumination, solar cells are allowed to cool and for a constant temperature, the current-voltage characteristic is drawn.

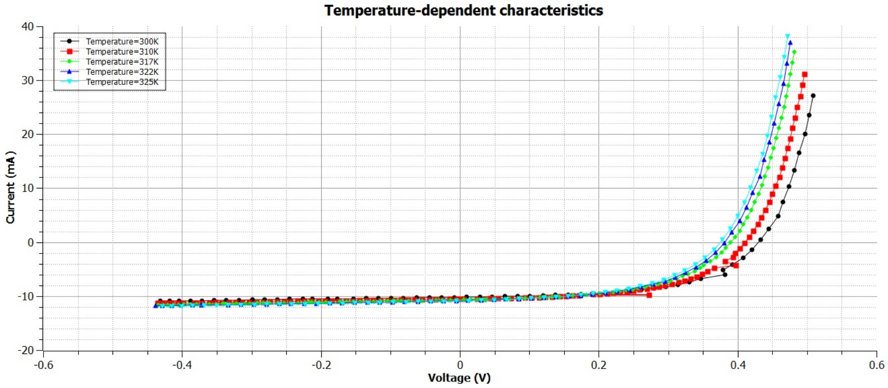


Figure 3.4: Temperature dependent I-V characteristics.

From the extrapolation of the open circuit voltage to $T = 0$, one finds the band gap of the given silicon solar cell. From fig OC voltage vs temp.jpg one find the linear fitting equation to be $y = -0.0022x + 1.1244$ where x represents the temperature and y being the open circuit voltage. At $T = 0$ i.e. when x=0 then y=1.1244 eV which approximately matches with the theoretical value of $1.17eV$ at 0 Kelvin.

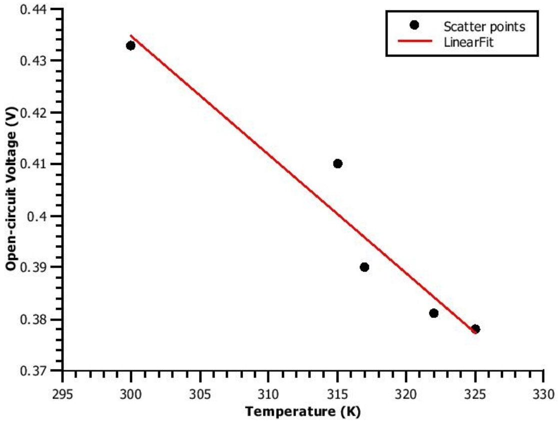
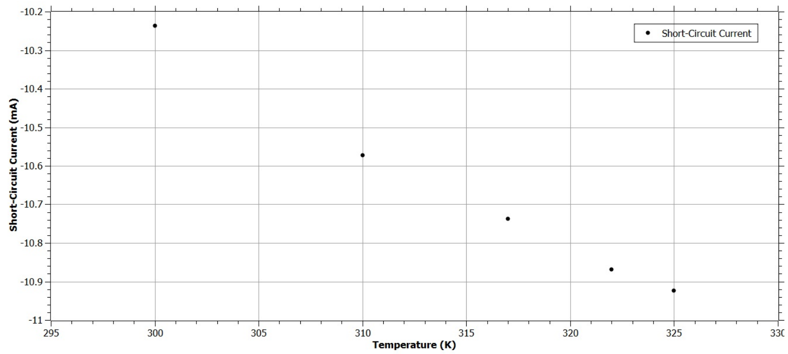
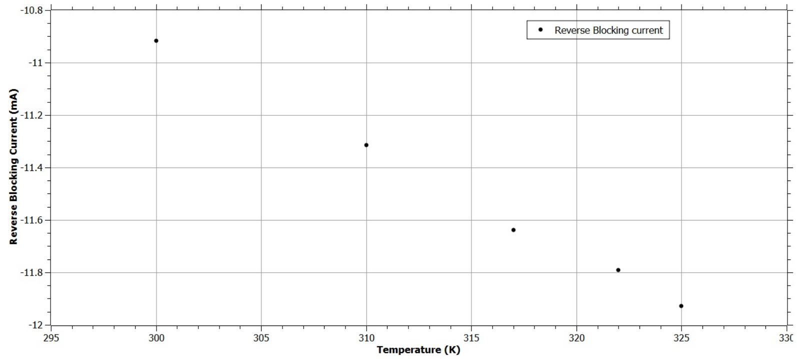


Figure 3.5: Open circuit voltage Vs temperature.

Both short circuit current and reverse blocking current as a function of temperature are shown in figure 3.6a and 3.6b. The short circuit current and reverse blocking current increase when temperature increases and due to temperature of solar cell increases, the open-circuit voltage also decreases implying that it is easier for electrons to be excited. Thus, at higher temperature, more electrons can move from valence band to conduction band in order to increase both short-circuit current and reverse-blocking current.



(a) Short circuit current vs temperature.



(b) Reverse blocking current Vs temperature.

Figure 3.6: Temperature dependent characteristics.

3.4 Comparison between solar cell and nuclear power

One block of a nuclear power plant has $P_{el} = 1GW = 10^9W$ and the incident power of solar radiation averaged over the whole year, day and night as well as all weather conditions is $120W/m^2$. Since efficiency is not calculated in this lab, 100% efficiency should be taken into account. Thus $area = P_{el}/P_{sun} = \frac{10^9W}{120W/m^2} = 8.333km^2$. This area is large and solar cells must be manufactured in order to have this area which is absurd.

4. Conclusion

More excited electrons can be generated by incident light energy which has a direct influence on the key elements of a solar cell like filling factor, efficiency etc. Absorption in the far infra red wavelength is observed here. There are two different ways to measure the band gap of a solar cell, by observing the short-circuit current as a function of wavelength or its dependence on the temperature. Time should be consumed in order to get the solar cells cooled down and the scanning of the spectrometer must be very accurate.

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