STUDY THE EFFECT OF ULTRAVIOLET RADIATION ON POLYCRYSTALLINE SILICON SOLAR CELL

By

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The undersigned hereby certify that they have read and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled "**Study the effect of ultraviolet radiation on polycrystalline silicon solar cell**" by **Nigatu Teklu** in partial fulfillment of the requirements for the degree of **Master of Science**.

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Abstract

The effect of ultraviolet(UV)radiation on polycrystalline silicon solar cell was studied. The reflectance spectrum, performance parameter and external quantum efficiency was analyzed by varying exposure time for different fluence of UV radiation. Reflectance spectrum showed increase for 10 minutes of exposure and starts to decrease and come back to nearly original value after 190 minutes exposure. Maximum potential power (P_{max}) showed no change for all fluence of UV radiation. Short circuit current density (J_{SC}) increase from $0.037\frac{A}{cm^2}$ to $0.041\frac{A}{cm^2}$ for 10 minutes of UV radiation exposure and external quantum efficiency (EQE) of polycrystalline silicon solar cell showed reduction for 10 minutes exposure and for the rest of fluences of UV radiation very small change of EQE was observed.

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Introduction

Solar cell some times referred to by more general term photovoltaic (PV) cells are semiconductor devices that convert sun light directly into electric current to produce usable electric power. Electrical energy is one of the most useful forms of energy that can be used for almost every thing. Man kind needs energy for living besides the energy in our food necessary to sustain our body and its function, more energy is used on average to make our life comfortable. Renewable energy sources such as wind, water and solar energy are abundant in nature and can be utilized with out harmful effect to the environment. One of the promising renewable energy source is energy from the sun.

The energy of the sun is created by nuclear fusion reaction of hydrogens which occur in side the sun at several million degree kelvins, the mass difference that occur in this process is converted to energy[1]. The solar energy that reach the surface of earth determined by ratio of diameter of the sun and earth and their distance apart. The intensity of solar radiation in free space at average distance of earth from the sun is defined as solar constant with value of $1353 w/m^2$[2]. Solar radiation attenuated as it transfer atmospheric layer, preventing substantial portion of it from reaching the earth surface. This phenomenon is due to absorption, scattering and reflection in upper atmosphere, with it's thin layer of ozone and lower atmosphere with which clouds of formation occurs and weather condition manifest themselves. This source of energy is much greater than any projected energy needs besides it is renewable and

non polluting. Solar energy has huge potential to meet the energy demand of the world[3].

Humans manipulated solar energy since 7^{th} century BC when magnifying glasses were used to concentrate sun's ray to make fire and burn ants. In 1839 Alexarder Becquerrel discovered photovoltaic effect during his study of two metallic electrodes in conductive solution[4]. This could be considered as start of solar cell industry. Photovoltaic effect is quantum electronic phenomenon as generation of electromotive force (voltage) with in range of material's non homogeneity during light illumination with appropriate wave length. This effect is high enough in specially prepared structure for conversion of electromagnetic radiation in to electricity.

The cell is smallest practical element that harnesses the photovoltaic effect to generate electricity. This cell can be made from many different materials in many different designs, although many materials are available, crystalline silicon is presently the most popular option for commercial cells[5]. Silicon is the second most abundant element in earth's crust. It occurs most often in nature as silicon dioxide and silicate. Sand and quartz are two of most common forms. Sand is generally too impure to be processed in to silicon. Many processing steps are conducted to bring silicon from its native one quartz to crystalline substrate[6]. The starting silicon for both PV and integrated circuit application is 99% pure metallurgical grade silicon obtained via carbon reduction of in arc furnace[7].

Silicon atom has fourteen electrons , their natural arrangement allows the outer four of these to be given to, accepted from or shared with other atoms . These outer four electrons called valance electrons. They play an important effect in photovoltaic effect. Large number of silicon atoms through their valance electrons bond together to form a crystal. In crystalline solid each silicon atom normally shares one of its four valance electrons in covalent bond with each of four neighboring silicon atoms. The solid silicon crystal is composed of regular series of units of five silicon atoms the

original atom plus the four other atoms with which it shares its valance electrons.

There are many reasons for dominance of crystalline silicon in photovoltaic industry. It's stable performance, low device manufacturing cost and mostly non toxic materials used in final product and its dominance in micro electronics industry. It has become by far most studied of all the semiconductor and many specialized process involving its use has been developed and refined over several decades, some of these process and much of accumulated knowledge have be directly transferred to photovoltaic applications with great benefit[8].

Single crystal, polycrystalline, ribbon and thin film solar cell are four types of crystalline solar cells. Polycrystalline silicon consisting of small grain of single crystal silicon. Polycrystalline silicon PV cells are less energy efficient than single crystalline silicon PV cells. The grain boundaries in polycrystalline silicon hinder the flow of electrons and reduce the power out put of the cell compared to single crystalline silicon cell. Polycrystalline silicon solar cell is stronger than that of single crystalline and it can be cut into one third the thickness of single crystal cells. Polycrystalline silicon cell has lower wafer cost and less strict growth requirement, however their lower manufacturing cost is offset by its lower cell efficiency[9].

The modern era of photovoltaic begin in 1954 in that year chapit et al reported a solar conversion efficiency of 6% for crystalline silicon solar cell[10]. Now a days laboratory conversion efficiency is around 25% production efficiency 12-15%[11]. PV cell efficiency is measured by proportion of available sun light energy that the cell converts to electrical energy. PV cell manufactures are improving their efficiency and reducing their production cost this makes PV energy more competitive with traditional sources of energy. One of greatest challenge for global economy is energy and search for alternative to reduce the reliance on coal and gas. The demand for energy is growing rapidly because of rapid increase in the world population and rise of standard of living. Majority of energy demand has been supplied by fossil fuel. The

use of fossil fuel for power generation cause pollution leads to climate change. The world is patiently waiting for alternative energy source to offset the damage caused by fossil fuel. Each kw produced by fossil fuel release up to 375kg NO_2 , 680kg SO_2 and 98,430kg CO_2 each year but PV cell generate power with out pollution[12].

There are three main areas in which commercially viable solar cell must exceed to make photovoltaic conversion of solar energy a useful contributor to our energy needs. They are cost, efficiency and operating life time clearly they are not independent but are mutually relate. Efficient solar cell must have long operating life time to repay both the financial cost and energy cost required for its initial production. Operating life time for polycrystalline solar cell is more than 20 years. Energy pay back is less than 5 years[13].

The dominant process that limit operating life time for terrestrial application are quite different from space application. Damage to crystal lattice by high energy particle fluxes present in space can degrade the life time[14]. For terrestrial polycrystalline silicon solar cells corrosion is main one to degradation. Terrestrial solar cells always appear in form of module. A module is a group of solar cells that are wired together in suitable electrical configuration and packed in a weather proof flat container. One side of module is transparent, allowing sun light to reach the solar cell. The module has electrical leads for connection to load.

The aim of this work is study the effect of ultraviolet radiation on polycrystalline silicon solar cell i.e surface reflection, current-voltage characteristics and incident photon conversion efficiency. Most irradiation studies on polycrystalline silicon solar cell have been performed with electrons, protons and heavy particles for space application[15,16,17 and 18], however I didn't see work done on effect of UV radiation on crystalline solar cell.

The motivations of this work are:-

1. Irradiating the surface of polycrystalline silicon solar cell by UV ray transfer high amount of energy to surface that may change the optical, electrical and structural properties of surface.

2. It only heat up the top surface of cell and modify surface properties.

3. UV radiation is less energetic than electron and proton radiation which have deteriorating effect on solar cell.

4. UV irradiation has ability to crystalline materials during fabrication process[19].It may show this property post fabrication.

5. UV radiation accounts $3-5\%$ of all solar radiation reaching the earth surface. It is reasonable to study the effect on polycrystalline silicon solar cell.

This experimental work study surface property (reflection from surface) before and after UV irradiation on silicon solar cell for monochromatic light, ranging from near UV radiation through visible to infrared region. Current-voltage response has been studied. Incident photon conversion efficiency of cell has been studied before and after UV irradiation. The first chapter is about physics of semiconductor especially silicon. The second chapter examines extrinsic semiconductor, pn junction and mechanism of charge carrier generation and recombination. Real solar cell was also discussed there. Chapter three devoted for instruments and method of experiment. The last one is about result of experiment and discussion.

Chapter 1

Semiconductor material

Direct transformation of light into electrical energy requires a semiconductor material. The semiconductor materials are solids which is in pure state insulate at temperature approaching absolute zero, but at higher temperature posses a clearly demonstrable conductivity. A remarkable property of semiconductor is that small concentration of impurity of dopant can have a drastic through very predictable effect on conductivity of crystal[20]. Common semiconductors that are widely used in electronic and optoelectronics applications are group IV elemental semiconductors (e.g Si and Ge). Group III -V Semiconductor compound (e.g AlAs, GaAs, GaP, GaN, InAs and InSb). Group II - VI compound(e.g ZnO, ZnS and ZnSe) and group IV- VI compounds (e.g PbS, PbS_2,and PbTe). This chapter discussed intrinsic semiconductor mainly silicon semiconductor's electrical property and crystallographic structure. The distinction of semiconductor material from other also discussed.

1.1 Silicon semiconductor

Crystallographic structure

Crystalline silicon is one of the most common material for photovoltaic device. The main factors that determine optical and electrical properties of semiconductors are related to chemical composition, crystallographic structures and presence of various defects. Group IV elemental semiconductors have diamond lattice structure that can be described as face centered cubic structure(FCC), and inside the cell there are four additional atoms totally there are eight atoms is cubic unit cell.

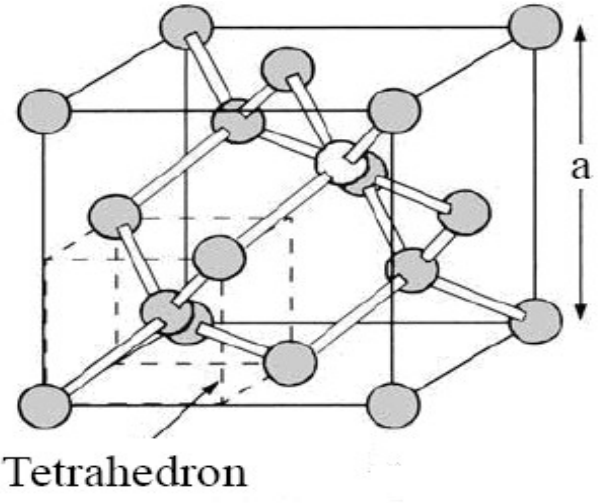

Figure 1.1: The diamond lattice structure with lattice distance a.

Every atom in this arrangement has four equally spaced neighbors in tetrahedral coordination. The diamond structure can also viewed as two interpenetrating FCC lattice displaced from each other along the cube's body diagonal by one fourth of its length[21].

Semiconductor materials like any other material may contain variety of defect which are introduced in a material during growth and processing. Defects are all types of deviations from ideal crystalline structure. It can be structural defect and

transient defect.

Structural defect includes

1. Point defect such as substitutional and interstitional impurity atom and vacancies.

2. One dimensional the defect such as dislocations.

3. Two dimensional planar defect such as surface, grain boundaries and stacking faults .

4. Three dimensional or volume defect such as voids and inclusions.

Transient defect are elementary excitations such as phonons. In real solids defect may interact and form a variety of possible combination. They may also act as attractive center for charge carriers recombination.

One of the main objective in semiconductor synthesis and device fabrication is reducing the undesirable defect densities to sufficiently low levels that don't influence semiconductor electrical, optical and mechanical properties of device performance[22].

1.2 Electronic band structure of solid

Electronic band structure can explain the distinction between metals, semiconductors and insulators. In crystalline materials electronic wave function of constituent atoms over lap in the formation of solid. Application of Pauli exclusion principle leads to splitting of discrete energy levels of isolated atoms into band of allowed electron level separated by forbidden energy gaps. The lower energy band is called valance band where as the upper band is conduction band. The energy difference between the top of valance band (E_V) and bottom of conduction band (V_C) is called energy gap (E_g) or band gap of material . It is most important parameter of material.

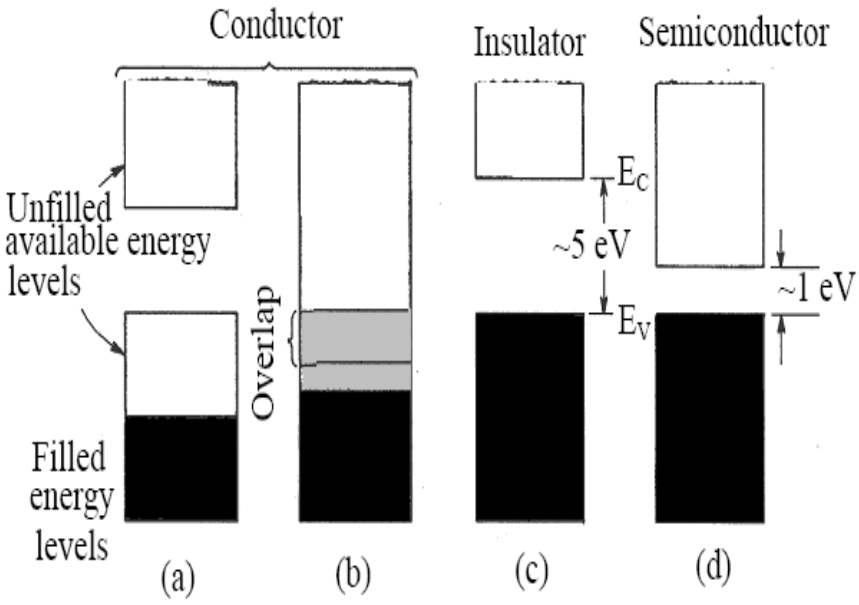

Figure 1.2: Energy band in crystalline solid at 0K (a) and (b) Conductor (c) Insulator (d) Semiconductor

The magnitude of energy gap distinguishes semiconductors from insulator and metal. These materials differ in terms of electron conductivity. Material with empty energy bands which don't contain electrons that contribute to electrical conductivity. In completely filled band all energy levels are occupied and electrons don't contribute to conductivity. Partially filled bands contain both electron and unoccupied energy level in the presence of applied field carriers can contribute to electrical conductivity of materials . The band gap of insulator is much larger than that of semiconductor's. Metals have no band gap since conduction and valance band overlap.

The Fermi energy and Fermi level (E_F) defines the reference energy for probability of occupation in electron state. In semiconductor and insulators E_F positioned in forbidden band. Electron affinity defined as energy difference between vacuum level and bottom of conduction band. Another important parameter is work function which is energy difference between vacuum level and Fermi level. Electron affinity is

constant for a given semiconductor where as work function depend on doping which affect Fermi level position[23].

In the presence of periodic crystal potential modifies electron properties result in electron mass that is different from the free electron mass (m_o). The effective mass (m^*) typically referred to experimentally determined values of electron mass. Effective mass of different semiconductor is slightly less or greater than free electron mass.

1.3 Free charge carriers in intrinsic semiconductor

Electrical property

An ideal intrinsic semiconductor is pure semiconductor with no impurity atoms and lattice defect in a crystal. Intrinsic semiconductor's valance band is full of electrons and conduction band is empty at 0k. At finite temperature, however, some electron acquire thermal energy and leave valance band to occupy conduction band, the valance band left with unoccupied states

when all valance band states are occupied the sum over all wave vector is zero.

$$\sum_{K_i \neq K_e} (K_i + K_e) = 0$$

Now in situation where electron at wave vector (K_e) missing the total wave vector

$$\sum_{K_i \neq K_e} K_i = -K_e \tag{1.3.1}$$

The missing state in wave vector of the system is called hole. Electrons are negative charge carriers and holes are positive charge carries. Electronic transition across band gap to conduction band result in spontaneous generation of holes in valance band and generated carries are described as electron - hole pair. As soon as charge carriers are formed recombination is set in action. An average time before

carriers recombine is called life time (τ) of carriers. Concentrations of electron (n) in conduction band and concentration of the holes (p) in valance band are equal during process of generation electron - hole pair .

Electrons and holes are referred as free charge carriers, in the presence of electric field (ξ) they attain drift velocity (V_d) and net carrier density (J)

$$V_d = -\mu\ J \tag{1.3.2}$$

Where μ mobility of charge carrier. It is measure of ease of motion for charge carrier in semiconductor

$$\mu = \frac{e\tau}{m^*} \tag{1.3.3}$$

mobility of electron is greater than mobility of hole due to inverse relationship between mobility and effective mass. The current density for electron and hole can be expressed as

$$J_n = -\ n\ q\ V_{dn} \tag{1.3.4}$$

$$J_p = \ p\ q\ V_{dp} \tag{1.3.5}$$

Thus the current densities for electrons and holes are in the same direction since the corresponding drift velocities are in opposite direction. Both electrons and holes contribute to current in intrinsic semiconductor

$$J = J_n + J_p$$

$$J = q(\mu_n n + \mu_p p)\xi$$

$$J = \sigma\xi \tag{1.3.6}$$

Where $\sigma = q(\mu_n n + \mu_p p)$ is bulk conductively. It is reciprocal of bulk resistivity.

Unintentional impurity or defect strongly influence the electron and hole transport through the bulk of the semiconductor material. They can act either as trap, where electrons and holes trapped, or as a generation-recombination center, where one charge carrier annihilates with carrier with the opposite charge.

1.4 Charge carrier concentration and energy distribution in intrinsic semiconductor

Electrons and holes are charge carrier in semiconductor materials. Optical and electrical properties of these materials depend on concentration of charge carriers. They are equal in intrinsic semiconductor. The probability of carrier concentration (occupancy of state) at energy E and density of available states are required to determine both carrier concentration and energy distribution . The occupation statistics of energy level by carriers is described by Fermi dirac distribution function. The probability of electron occupying a state at energy E

$$f_n(E) = \frac{1}{exp\ [\frac{E-E_F}{K_B T}] + 1} \tag{1.4.1}$$

Where E_F is called Fermi energy

For the hole the distribution function is

$$f_p(E) = 1 - f_n(E) \tag{1.4.2}$$

In semiconductor, mobile electrons are those occupying the energy state E greater than E_c. Electrons concentration in conduction band depends on density of state for electrons in conduction band. It is number of available state per unit volume per unit energy.

$$n = \int_{E_C}^{\infty} g_n(E) f_n(E) dE$$

Where $g_n(E)$ is density of state of electron

$$g_n(E) = 4\pi \ [\frac{2m_e^*}{h^2}]^{\frac{3}{2}} (E - E_C)^{\frac{1}{2}}$$

Similarly for holes in valance band, the total number of holes can be expressed as

$$P = \int_{-\infty}^{E_V} g_p(E) f_p(E) dE$$

Where $g_p(E)$ is density of states for holes

$$g_p(E) = 4\pi \ [\frac{2m_h^*}{h^2}]^{\frac{3}{2}} (E_V - E)^{\frac{1}{2}}$$

The Fermi dirac function can be expressed in more simplified form since K_BT at room temperature as about $0.026eV$. $E - E_F >> K_BT$ and espesifically $E - E_F > 3K_BT$ thus the Fermi dirac function reduced to classical Maxwell Botzmann function[24].

$$f_n(E) = \frac{1}{exp \ [\frac{E-E_F}{K_BT}] + 1} \ \cong \ exp \ [\frac{-(E - E_F)}{K_BT}]$$

Concentration of electron in conduction band becomes

$$n = N_C \ exp \ [\frac{-(E_C - E_F)}{K_BT}] \tag{1.4.3}$$

Where $N_C = 2 \ [\frac{2\pi \ m_e^* K_B T}{h^2}]^{\frac{3}{2}}$ is effective density of statistics at bottom of conduction band.

Similarly hole concentration

$$p = N_V \ exp \ [\frac{E_V - E_F}{K_BT}] \tag{1.4.4}$$

where $N_V = 2[\frac{2\pi m_h^* K_B T}{h^2}]^{\frac{3}{2}}$ is effective density of statistics at top of valance band. Intrinsic semiconductor are non degenerate that is

$$n = p = n_i$$

$$n_i = N_C \ exp \ [\frac{E_{Fi} - E_C)}{K_B T}]$$

$$n_i = N_V \ exp \ [\frac{E_V - E_{Fi})}{K_B T}]$$

where $E_F = E_{Fi}$

$$N_C = n_i \ exp \ [\frac{E_C - E_{Fi}}{K_B T}] \tag{1.4.5}$$

$$N_V = n_i \ exp \ [\frac{E_{Fi} - E_V}{K_B T}] \tag{1.4.6}$$

The intrinsic fermi energy can be derived from from above equations

$$E_{Fi} = [\frac{E_C - E_V}{2}] + [\frac{K_B T}{2}] \ \ln \ [\frac{N_V}{N_C}] \tag{1.4.7}$$

$$E_{Fi} = [\frac{E_C + E_V}{2}] + [\frac{3K_B T}{4}] \ \ln \ [\frac{m_h^*}{m_e^*}]$$

The equilibrium density of electron and hole in intrinsic semiconductor

$$np = n_i^2 = N_V . N_C \ exp \ [\frac{-E_g}{K_B T}] \tag{1.4.8}$$

This relation ship is known as mass action law

$$n_i == \sqrt{N_V N_C} \ exp \ [\frac{-E_g}{2K_B T}]$$

The intrinsic carrier concentration is a strong function of temperature.

Chapter 2

Solar cell mechanism and performance

The solar cell are actually semiconductor device made of two thin layers of specially treated semiconductor material. In a semiconductor some impurities are deliberately introduced to produce material with desired properties, in this case, the material is called extrinsic semiconductor and the process of putting impurities in the lattice is called doping. Impurities that contribute electrons to conduction band are called donors and these that supply holes to valance band are acceptors. The mobility of charge carrier's in valence and conduction band is greatly affected by presence of intentionally or unintentionally introduced impurities i.e. foreign atoms incorporated in a crystal structure of semiconductor. In a solar cell commonly silicon solar cell, when light fall on the cell, photons are absorbed and electrons are set free. Excess electrons accumulates on negative side of the cell. If the wire connected between the two layers, one positive and the other negative a flow of electrons occurs. This becomes electrical source that can be utilized. In this chapter intentional impurity in a semiconductor, junction property of diode, mechanism of electron - hole pair generation and performance parameters of solar cell are discussed.

2.1 Donors and acceptors in semiconductor

Extrinsic semiconductor

Donors are substitutional impurities that have a higher valance than the atom of host materials. An electron is donated to conduction band with out creating hole in valance band when donor impurities is ionized, this leads to excess of mobile electron and the material is referred as n-type.

Acceptor impurities have lower valance than the host which leads to incomplete atomic bonding in the lattice. The incomplete bonds capture electrons i.e. supply holes to valance bond without creating hole in conduction band. This semiconductor referred to as p-type.

The purpose of n-type doping is to produce an abundance of electrons in the material. Consider the case of silicon. It has four valance electrons each of which is covalently bonded with one of four adjacent silicon atoms. If an atom with five valance electron such as those from group V of periodic table such as Phosphorus, Arsenic or Antimony is incorporated into crystal lattice in a place of silicon atom then that atom will have four covalent bonds and left one unbounded electron. This extra electron is only weakly bound to atom and can easily excited into conduction band leaving a positively charged immobile atom behind.

A p-type doping creates an abundance of holes, in case of silicon trivalent atom such as boron, Aluminum, Indium or Gallium is substituted in a crystal lattice. This results that one electron is missing from one of four covalent bonds normal for silicon lattice. The dopant atom accept electron causing a loss of bond from neighboring atom and resulting in the formation of hole. The negatively charged acceptor atom after an electron joins its valance shell is immobile and does not contribute to conduction process. The hole left behind by that electron is counted in hole concentration.

At sufficiently low temperature holes and electrons become localized at acceptor

and donor center respectively, which become neutral. Donor and acceptor levels are located in the forbidden energy gap. The energy level in gap of semiconductor can be categorized as shallow and deep levels according to depth from nearest band edge. The donors and acceptors are shallow when their levels are close to bottom of conduction band and top of valance band respectively. Shallow impurities are those that require typically energies corresponding to about thermal energy to ionize. On the other hand deep impurities require higher energies in order to ionize. They are center for electrons and holes recombination instead of contributor of free carrier. Typically for shallow impurities at room temperature almost the entire donor-acceptor sites are ionized. Free carrier density corresponding to impurity concentrations

$$n = N_D \cong N^+$$

$$p = N_A \cong N^-$$

In an extrinsic semiconductor it is great importance to determine the carrier concentration in terms of Fermi level and other semiconductor material's parameter. Equations (1.4.5) and (1.4.6) can be rearranged to drive another form of equation for thermal equilibrium concentrations of electrons and holes[25].

$$n = N_C.\ exp\ [\frac{-(E_C - E_{Fi}) + (E_F - E_{Fi})}{K_B T}]$$

$$n = N_C.\ exp\ [\frac{-(E_C - E_{Fi})}{K_B T}]\ .\ exp\ \frac{(E_F - E_{Fi})}{K_B T}$$

The intrinsic carrier concentration

$$n_i = N_C.\ exp \frac{-(E_C - E_{Fi})}{K_B T}$$

so that the thermal equilibrium electron concentration can be written as

$$n = n_i.\ exp\ \frac{(E_F - E_{Fi})}{K_B T} \tag{2.1.1}$$

similarly

$$n_i = N_V.\ exp\frac{(E_V - E_{Fi})}{K_B T}$$

$$p = n_i.\ exp\ [\frac{-(E_F - E_{Fi})}{K_B T}] \tag{2.1.2}$$

For donor-doped (n type) and accepter-doped (p type) non degenerate semiconductors at equilibrium the Fermi level can be related to carrier concentration for n and p type respectively

$$E_F = E_i + K_B T\ \ln\ [\frac{N_D}{n_i}] \tag{2.1.3}$$

$$E_F = E_i - K_B T\ \ln\ [\frac{N_A}{n_i}] \tag{2.1.4}$$

2.2 pn-junction

To understand the function of semiconductor device and thus of solar cell a precise understanding of process with pn-junction is crucial. A pn-junction is made by incorporating acceptor atoms in one part of a crystal and donor atom in other, i.e a crystal is separated into p doped and n doped material. The n side consists of free electrons and ionized donor atoms while the p side consists of free holes and ionized acceptor atoms. Holes concentrated in p side would like to diffuse to fill crystal uniformly and also electrons would like diffuse to n side. This cause bending of conduction band edge and valance band edge leads to constant fermi level through out entire system. A transient diffusion current of electrons from n doped to p doped semiconductor leads to positively charged region in n type semiconductor while hole diffusion from p doped to n doped region cause a negative space charge in p region.

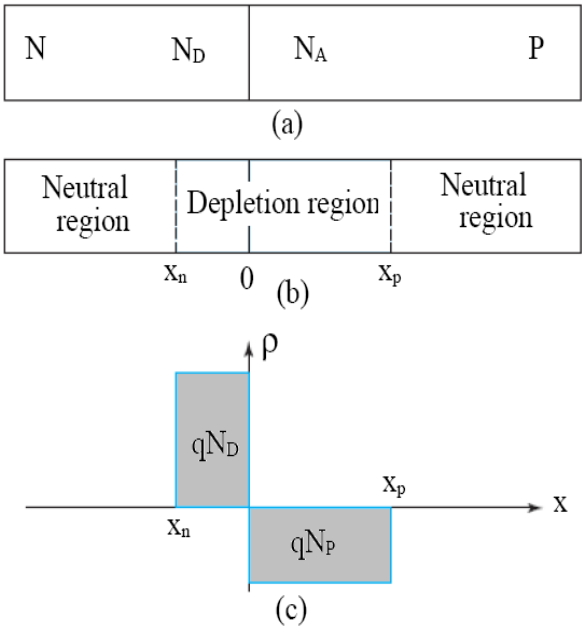

Figure 2.1: (a) Step pn junction; (b) Depletion approximation; (c) Space charge profile.

The net positive and negative charges in n and p region induce an electric field in depletion region in direction from positive to negative charge or from n to p region. The built in electric field causes electrons and holes is depletion region drift in opposite direction to diffusion. Eventually equilibrium is formed when force of this developing built in field become exactly equal and opposite of diffusion force. Region far from metallurgical junction where space charge density is zero and Fermi level is flat is called quasi neutral region (QNR). The depletion region's mass action law $n_i^2 = np$ attained at equilibrium.

Electrons and holes charge density in depletion region

$$\rho(x) = qN_D \qquad for \ -x_n \leq \ x \ \leq \ 0$$

$$\rho(x) = -qN_A \qquad for \ 0 \leq \ x \ \leq \ x_p$$

Electric field can be found integrating Poisson's equation

$$\frac{d\xi}{dx} = -\frac{\rho(x)}{\epsilon\varepsilon_o}$$

$$\xi = \frac{-qN_D}{\varepsilon_s}\ (x_n - x) \qquad for\ -x_n \leq\ x\ \leq\ 0 \tag{2.2.1}$$

$$\xi = \frac{-qN_A}{\varepsilon_s}\ (x + x_p) \qquad for\ 0 \leq\ x\ \leq\ x_p \tag{2.2.2}$$

Electric field is continuous through out depletion region

$$N_A.x_p = N_D.x_n \tag{2.2.3}$$

Free charge carriers see a potential barrier while trying to move to other region. This potential barrier referred as build in potential barrier V_{bi} that exist across depletion region even at thermal equilibrium.

V_{bi} can be determined from two view points the first was diffusions of carries yielding a charge density which in turn produced an electric field and hence a potential difference

$$V_{bi} = -\int_{-x_p}^{x_n} \xi(x)dx$$

$$V_{bi} = \frac{q}{2\varepsilon_s}\ (N_A.x_n^2 + N_D.x_p^2) \tag{2.2.4}$$

The second equivalent view point was based on energy band diagram and consistency of E_F. The intrinsic Fermi level is equidistance from conduction band edge through junction. V_{bi} can be determined as difference between intrinsic Fermi level in p and n regions

$$V_{bi} = (E_{FP} - E_F) + (E_F - E_{FN})$$

From this

$$V_{bi} = (\frac{K_BT}{q}\ \ln\ \frac{N_A}{n_i}) + (\frac{K_BT}{q}\ \ln\ \frac{N_D}{n_i})$$

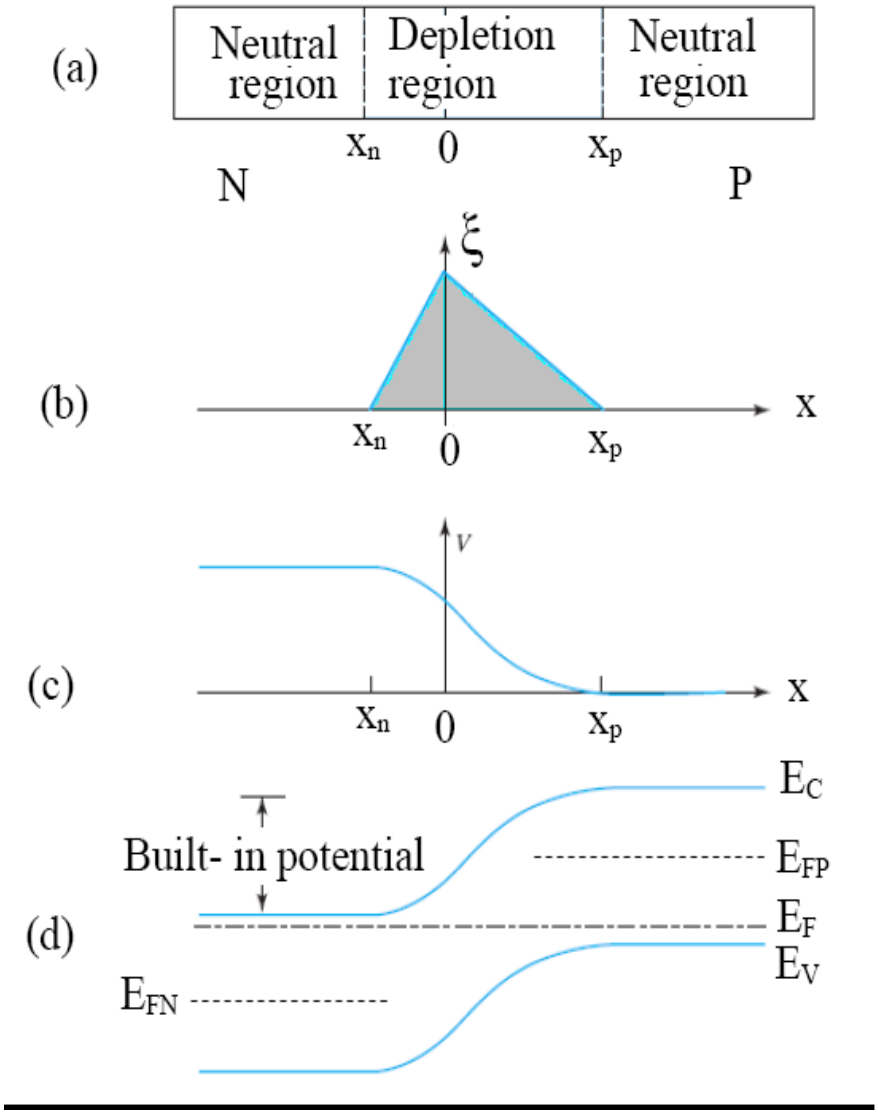

Figure 2.2: (a) Step pn junction; (b) Electric field; (c) Electric potential; (d) Energy band diagram

$$V_{bi} = \frac{K_B T}{q} \ \ln \ \frac{N_A.N_D}{n_i^2} \tag{2.2.5}$$

A pn junction is forward bias when applied voltage V_A has positive potential on the p region and negative potential on the n region. This applied voltage reduce voltage across depletion region since V_A is opposite in polarity relative to V_{bi}

$$V_j = V_{bj} - V_A$$

Reverse bias requires that the applied voltage be less than zero i.e is opposite polarity to forward bias

$$V_j = V_{bj} + V_A$$

For thermal equilibrium the junction potential was V_{bi} and depletion region width W could be determined.

$$W = x_p + x_n$$

$$W = \mid \frac{2\varepsilon_o V_{bi}}{q} (\frac{N_A + N_D}{N_A N_D}) \mid^{\frac{1}{2}}$$

Now in case of applied voltage V is replaced by junction potential V_j

$$W = \mid \frac{2\varepsilon_o V_j}{q} (\frac{N_A + N_D}{N_A.N_D}) \mid^{\frac{1}{2}} \tag{2.2.6}$$

Thus space charge width become narrower in forward bias and wider in reverse bias mode with respect to its thermal equilibrium width[26].

2.2.1 Dark diode current density

Applying voltage to pn junction semiconductor allows an increase in rate at which majority carrier diffuse across the junction and become minority carrier. Holes that

diffuse from p region to n region are called injected minority carrier holes in n region, while for electron that diffuse from n region to p region are injected minority carrier electrons for p region. Diffusion current densities for holes and electrons at edges of depletion region of pn junction semiconductor[27].

$$J_p(x_p) = \frac{qD_p p_{po}}{L_p}\ (exp\ \frac{eV_A}{K_B T} - 1)$$

$$J_p(-x_n) = \frac{qD_n n_{no}}{L_n}\ (exp\ \frac{eV_A}{K_B T} - 1)$$

Where $L_{n,p} = \sqrt{D_{n,p}\tau_{n,p}}$ mean lengths for minority carrier recombination.

These injection current densities that diffuse in dark are called dark diode current density.

$$J = J_p(-x_n) + J_n(x_p)$$

$$J = q(\frac{D_p p_{po}}{L_p}\ +\ \frac{D_n n_{no}}{L_n})\ (exp\ \frac{eV_A}{K_B T} - 1) \tag{2.2.7}$$

$$J_o = q(\frac{D_p p_{po}}{L_p}\ +\ \frac{D_n n_{no}}{L_n}) \tag{2.2.8}$$

Where J_o is saturation current density

2.3 Photovoltaic cell

A solar cell is semiconductor device that converts sun light directly into electricity via photovoltaic effect. The photovoltaic effect is physical phenomenon that generates voltage across the junction from absorption of photon.

When sun light fall on the surface of semiconductor with pn junction the built in field at the junction separate photo generated carriers in bulk. Electrons are collected in n region and holes in p region result in voltage generation across the junction. A generated voltage drives current through electrodes to external load.

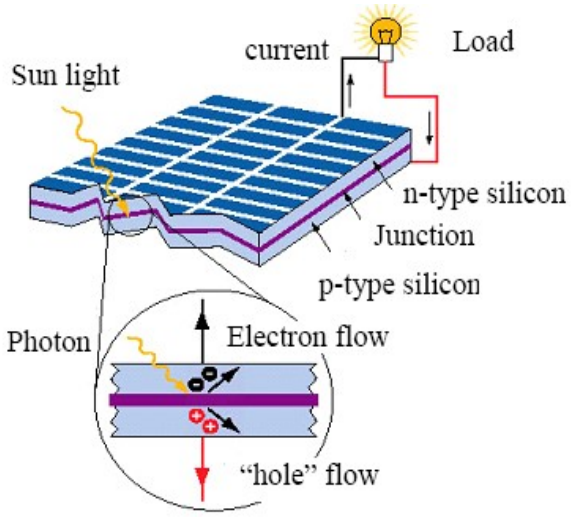

Figure 2.3: Typical crystalline pn junction silicon solar cell.

Light impinging on semiconductor is subject to number of optical interaction before it is absorbed. First, a fraction of incident light is reflected at outer surface; the remaining transmitted. A fraction from transmitted light scatter from crystal imperfections, phonons and other quasi particles, then the fraction with in semiconductor is absorbed by elementary excitation process, depending on photon energy.

Unlike metal semiconductor (solar cell) display what is for them characteristic absorption behavior. Photon only with energy larger than band gap (Eg) is absorbed.

	$E_g(0K)(eV)$	$E_g(300K)(eV)$
Silicon	1.16	1.12
Germanium	0.741	0.66
Gallium Arsenide	1.519	1.411

Table 2.1: Band gap of typical semiconductors[28].

The unabsorbed fraction exit through semiconductor back surface after partial reflection. The back surface of most solar cell (and solar cell used for this experiment) coated with silver to totaly internally reflect the incoming light.

Reflection is the process of which light is incident on the surface interact with the surface such that it leaves on the incident side with out change in frequency. Reflection is a loss in a solar cell, to harvest more from solar radiation reflection loss at the surface must be minimized. The common solution for reflection loss is using appropriate antireflection coating[29]. Antireflection coating usually coated on front surface to reduce reflectance spectrum of the surface. Reflectance(r) is defined to be the ratio of reflected power (or flux) to incident power.

$$r = \frac{I_r}{I_i} \tag{2.3.1}$$

Some photon may travel a considerable distance in a solar cell before being absorbed. The light intensity decreases exponentially as it passes through the surface of cell

$$I(x) = I(x_o)exp - \alpha(x - x_o) \tag{2.3.2}$$

where α is absorption coefficient it determine how far below the surface of light of a given wave length is absorbed. $\frac{1}{\alpha}$ may be called light penetration depth. A solar cell must have a thickness significantly larger than light penetration depth. A polycrystalline bulk silicon solar cell should not be thinner than $30\mu m$ to absorb most photon with energy above Eg[30].

2.3.1 Electromagnetic solar spectrum

All energy carried by photon is referred as electromagnetic energy and spans all possible values for wave length. The sun emit energies covering a range of wave length of electromagnetic spectrum. The spectrum in the space as seen from satellite is referred as air mass zero (AMO) with incident power $1353w/m^2$. The air mass gives information about the amount of air mass radiation pass to through. AM1.5 that is

the sun is 45^o above the horizon. It represents a satisfactory energy weight average for territorial application. The total incident power for AM1.5 is $844w/m^2$. The peak region of electromagnetic spectrum of sun is from 400-700nm which is visible range of spectrum. There is large number of photons through most of infrared region. A silicon solar cell utilize all visible and much of infrared region of spectrum. A semiconductor with narrower band gap is more suitable for utilization of wider fraction of light[31].

2.3.2 Absorption of light

Absorption refers here lattice absorption of photons by excitation of electron from valance band up into conduction band, leaving a hole in valance band. Energy and momentum must be conserved in such transition[32]. Minimum of conduction band and maximum of valance band lie at different crystal momentum in the indirect band gap semiconductor, like Si and Ge[33]. The absorption behavior, the direct transition from valance band to conduction band requires involvement of lattice vibration that is phonon for conservation of energy and momentum.

Light of appropriate wave length create electron-hole pair in a solar cell, the reverse and non advantageous process a recombination of electrons and holes could appear. In case of silicon which is widely used in photovoltaic application recombination takes place via defect center in volume of semiconductor constituting the photovoltaic structure as well as entire surface[34].

A solar cell produces a current density (J) in bias mode under illumination in response to absorbed optical power. This current density in cell incorporate dark current density that has been derived for ideal diode in previous chapter, however, here ideality factor (n) which measure how close to ideal is incorporated by replacing

$$\frac{q}{K_B T} \quad by \quad \frac{q}{nK_B T}$$

The total current is

$$J = J_o(exp\frac{eV_A}{nK_BT} - 1) - J_{ph} \tag{2.3.3}$$

where J_{ph} is photogenerated current which can be represented by

$$J_{ph} = qG(W + L_n + L_p)$$

where G is generation rate. W is width of depletion region and $L_n and L_p$ are diffusion Length of charge carriers.

2.3.3 Equivalent circuit model represent a real solar cell

The photogenerated mechanism is represented by current generator on the left side of circuit. The dark recombination mechanism represented by diode. The current generator and diode are oriented in apposite direction.

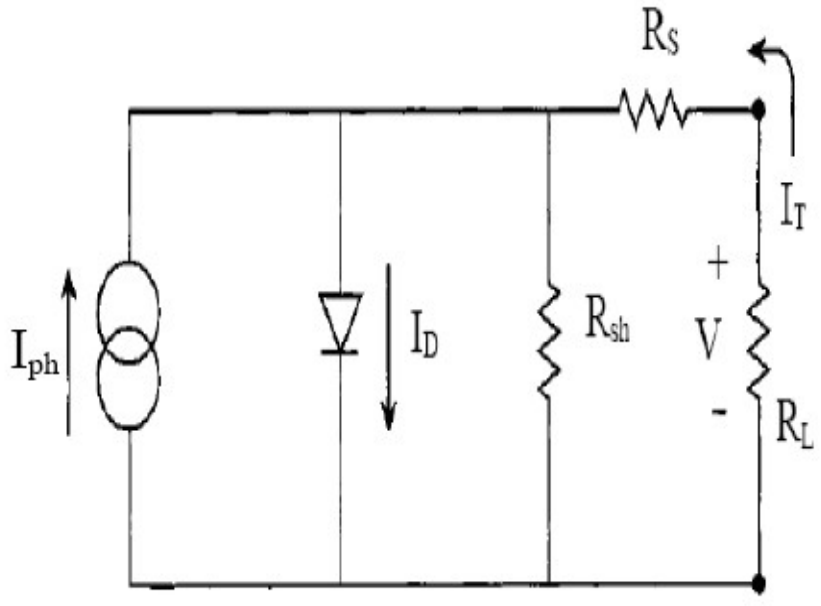

Figure 2.4: Schematic of equivalent circuit model for a p-n photovoltaic cell.

The equivalent circuit model has two resistors and external load R. R_{SH} represents any parallel high conductivity (shunts) through solar cell it could be caused by crystal damage. R_S represents series resistance on top of surface of a cell. It caused by surface grids that collect charge carrier and resistive contact of electrodes. They are strictly parasitic. R_S has to be small and R_{SH} should have to be large as possible to reduce loss for efficient cell. When parasitic resistors are included the current would be

$$J = J_o(exp(q(V + \frac{J_A R_s}{nK_B T} - 1)) - J_{sc} + \frac{V + JR_s}{R_{sh}} \tag{2.3.4}$$

2.3.4 The current density-voltage characteristics of solar cell

These are variation of current density (J) as function of voltage (V) for solar cell in dark and under illumination. For the purpose of comparison with J-V characteristics the voltages are the same for both cases. The dark characteristics given by equation (2.2.7) and lower curve shows the performance when a cell exposed to light. This curve is given by equation (2.3.3). The portion of the curve in fourth quadrant is region of power generation.

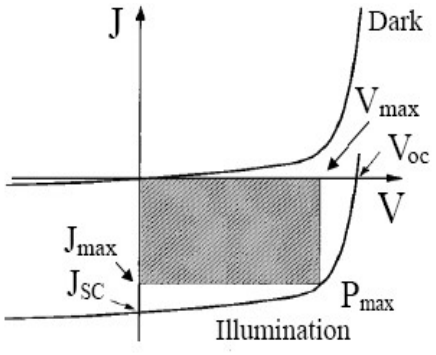

Figure 2.5: $J - V$ characteristics of solar cell under dark and under illumination. Determination of maximum out put is indicated.

The J-V characteristics curves are used to describe the following most important

parameter of solar cell, these are:-

1. Short circuit current density (J_{SC}). As it's name indicate the current density that is obtained under illumination while the load is shorted out, that is where there is no voltage in a cell. Ideally it is equal to photo generated current.

$$J_{sc} = J_{ph} \tag{2.3.5}$$

2. Open circuit voltage (V_{oc}). It is a measure of how strongly the separated photo generated charge can bias the junction at any given level of illumination. Analytical expression for V_{oc} using equation (2.3.3) with the circuit opened yields

$$V_{oc} = \frac{nK_BT}{q}.\ln(1 + \frac{J_{sc}}{J_o}) \tag{2.3.6}$$

This equation shows V_{oc} of cell increase as saturation current decrease

3. Fill factor (FF). It is the ratio of maximum power delivered to external circuit to potential power. Optimal power out put requires a suitable load resistance which corresponds to V/I where V and I are by definition the voltage and current at optimal operating point respectively.

$$P_{max} = I_{max}\ .\ V_{max}$$

$$FF = \frac{J_{max}\ .\ V_{max}}{V_{oc}\ .\ J_{sc}} \tag{2.3.7}$$

The fill factor also named by graphical representation. It indicate how much area underneath the J-V characteristics is filled by rectangle in relation to rectangle formed by V_{oc} and I_{sc}

4. Efficiency (η). It is ratio of photovoltaic power generated by cell to luminous power falling on it[35]

$$\eta = \frac{I_{max} \,.\, V_{max}}{P_{in}} \,.\, 100\% \tag{2.3.8}$$

	Symbol	Unit	Determined by
Open circuit voltage	V_{oc}	V	$J = 0$
Short circuit current density	J_{sc}	$\frac{A}{cm^2}$	$V = 0$
Maximum power	P_{max}	W	$(JV)_{max}$
Maximum power voltage	V_{max}	V	$Vat(JV)_{max}$
Maximum power current density	J_{max}	$\frac{A}{cm^2}$	$Jat(JV)_{max}$
Fill factor	FF	%	$\frac{(JV)_{max}}{(V_{oc}J_{sc})}$

Table 2.2: Basic $J - V$ performance parameters.

One extension of regular J-V measurement is the measurement of wave length dependent current response, typically performed at zero bias. This is referred as quantum efficiency (QE) represents fraction of photons of wave length λ that are converted into electron-hole pairs collected as current. The "external" quantum efficiency of a solar cell includes the effect of optical losses such as transmission and reflection. "Internal" quantum efficiency refers to the efficiency with which photons that are not reflected or transmitted out of the cell can generate collectable carriers.

Incident photon conversion efficiency(IPCE):- It gives us information of spectral convergence and efficiency of device to convert monochromatic light into electrons. The short circuit current density at every wave length defines the spectral response (SR) of solar cell.

$$SR = \frac{J_{sc}}{P_{in}} \tag{2.3.9}$$

The IPCE is also known as external quantum efficiency (EQE). It can be determined by measuring photoinduced current density of solar cell under illumination from an incident monochromatic light under short circuit conditions.

$$EQE(\lambda) = \frac{E_{ph}(\lambda)\ .\ SR}{q}$$

$$= \frac{hC}{q\lambda}\ .\ \frac{J_{sc}}{P_{in}}$$

$$= \frac{1240}{\lambda}\ .\ \frac{J_{sc}}{P_{in}} \tag{2.3.10}$$

2.4 Ultraviolet radiation

Ultraviolet radiation is portion of electromagnetic radiation with wave length shorter than that of visible but larger than X rays in range of 10-400nm and energy from 3 eV to 124 eV. Long exposure for human being is harmful due to its high energy. It may cause skin cancer and corneal damage. Ultraviolet region contribute not more than 10% of solar energy reaching on top of atmosphere . UV radiant with wave length less than 250nm almost entirely absorbed by atmospheric oxygen and ozone. Radiation of wave length between 280nm and 315nm absorbed efficiently but not completely by ozone. The atmospheric ozone absorption of UV radiation with wave length greater than 315nm is comparatively small[36]. UV radiation in its unique portion accounts for 3 to 5% of all solar radiation reaching the earth[37]. Electromagnetic radiation reaching the surface of earth expressed in terms of irradiance density denoting radiant power per unit area reaching the surface. The practical application of UV radiation include water purification and sterilization of insects. UV radiation could be produced from high and low pressure mercury vapor lamps. UV radiation interact with polycrystalline silicon solar cell like any other electromagnetic radiation. It is absorbed by the silicon crystal and energy of it transferred to solar cell. The energy per unit area per unit time, flowing perpendicularly into surface in free space given by poything vector $\overrightarrow{S}$

$$\overrightarrow{S} = c^2\varepsilon_o(\overrightarrow{E}X\overrightarrow{B}) \tag{2.4.1}$$

and electromagnetic radiation radiation wave considering plane wave electric field, and $E = cB$

$$< S >= c\varepsilon_o < E_o^2 > \tag{2.4.2}$$

The energy transferred to the surface when radiations fall on it related to E^2. Fluence of UV radiation is intensity of radiation multiplied by elongation time. Electromagnetic wave aside from carrying energy also carries momentum. UV light irradiance on solar cell surface impart momentum to electron in material with subsequently transmitted to lattice structure as whole[38].

Chapter 3

Instruments and methods of experiment

Three measurements have been taken in this experimental work before and after the sample irradiated by UV ray. They are reflection measurement, I-V response measurements and short circuit current with respect to wave length measurement. Instruments that are used for these work are listed as follows; Lock - in - amplifier, monochromator, Xenon arc lamp radiation source, filter, chopper, optical detector, electrochemical analyzer and 250W quartz tungsten halogen lamp radiation source regulated by oriel power source. Each of these instruments and experimental set ups are discussed below.

3.1 Instruments

3.1.1 Xenon arc lamp radiation source

It is source for continuous spectrum of light ranging from ultraviolet through visible to infrared. It uses Xenon gas inside a tube for generation of light. In order to achieve maximum efficiency the Xenon gas inside the lamp is maintained at extremely high pressure large care have to be taken not to dropped or rapture while in service.

3.1.2 Filter

It is optical device used to absorb or reject radiation of certain frequencies while allowing other to pass. A colored glass filters are wave length selective absorber. Absorption occurs when electric field of light wave interact with absorbing atom or molecule in an oscillating dipole interaction. The photon absorbed and atom of molecules is placed in excited state. This process occur only resonant wave length. The absorber excitation energy is dissipated as heat.

3.1.3 Optical Chopper

It is mechanical devices that physically block a light beam of some type. Rotating optical chopper is used commonly. A metal disk with sleets etched into it is mounted on DC motor and rotated. The disk is placed in path of light beam which will then cause the beam to be periodically interrupted by blocking part of a disk.

3.1.4 Optical detector

It is a transducer that converts an optical signal into electrical signal. It does this by generating electrical current proportional to intensity of incident optical radiation.

3.1.5 Quartz tungsten halogen lamp

It is popular visible and near infrared source because of their smooth spectral curve and stable output.

3.1.6 Lock - in - amplifier

Lock - in - amplifier is interfaced with a PC and is controlled by Lab view (National Instruments program) it used to detect and measure very small AC signal, accurate

measurements can be made even when the small signal obscured by noise source may thousands of time larger. Lock - in - amplifiers use the component of signal at specific reference frequency and phase. Noise signal at frequencies other than reference frequency are rejected and do not affect the measurement. The Lock - in - amplifier can be divided into four sections signal channel, reference channel, phase sensitive detector and DC amplifier with low pass filter

In the signal channel the input signal (and noise) is conditioned by low noise pre amplifier and post amplifier with filter sandwich in between.

The reference channel transform the externally applied reference to suitable square wave at reference frequency (ω_r)

phase sensitive detector or synchronous demodulator is actually the heart of instruments. As mentioned above Lock - in - amplifier requires reference frequency and it detect the response from the sample (experiment) at reference frequency. The output signal from signal channel inform of $V_{sig}\ sin(\omega_r t\ +\ \theta_{sig})$ where V_{sig} is signal amplified ω_r and θ_{sig} is signal frequency and is signal phase. Lock - in - amplifiers generate its own internal reference $V_L\ sin(\omega_L t\ +\ \theta_{ref})$ that is phase locked to external reference. The phase sensitive detector multiplies these two signal (The lock - in - amplifier signal and lock - in reference). The output is again two AC signal are at difference frequency $\omega_r\ -\ \omega_L$ and the other at sum frequency $\omega_r\ +\ \omega_L$.

Low pass filters, filters out the AC signal of $\omega_r\ \neq\ \omega_L$ noting left since both of them are AC signal, however of $\omega_r\ =\ \omega_L$ the difference frequency component will be DC signal. The DC signal proportional to signal amplitude.

Non synchronous inputs (noise) share no common frequencies with reference and will not contribute to DC component to phase sensitive detector output, when the output is passed through low pass filter to remove the AC fluctuation. Noise is represented by varying signal at all frequencies. The ideal lock - in only responds the noise at reference frequency. Noise at other frequency is removed by low pass filter

following synchronous demodulator (phase sensitive detector). This is advantage that lock - in - amplifier provides only inputs with frequencies at reference results in an output[39].

3.1.7 Monochromator

It is optical subassemblies used to isolate narrow portion of light spectrum. It accept wider range of wave length available at the input from the light or laser source and output monochromatic light. Monochromators generally consists of several parts of component for dispersion of radiation. Entrance, exit slit, collimator, focusing element and grating are the main ones. The dispersion or separation of different wave length is achieved by grating. It consists of substrate usually glass, ruled with series of parallel grooved that cover the grating surface.

3.1.8 Electrochemical analyzer

This instrument controlled by an external personal computer under windows environment using its own program Chi630a. The instrument is capable of measuring current down to Pico ampere and provides different techniques like Linear sweep voltmetry and Bulk electrolysis.

3.2 Experimental set up and procedures

3.2.1 Surface reflection measurement

Reflected power from the surface of sample (solar cell) was measured using monochromator, detector, chopper and lock-in-amplifier. The set up for this experiment shown in figure (3.1)

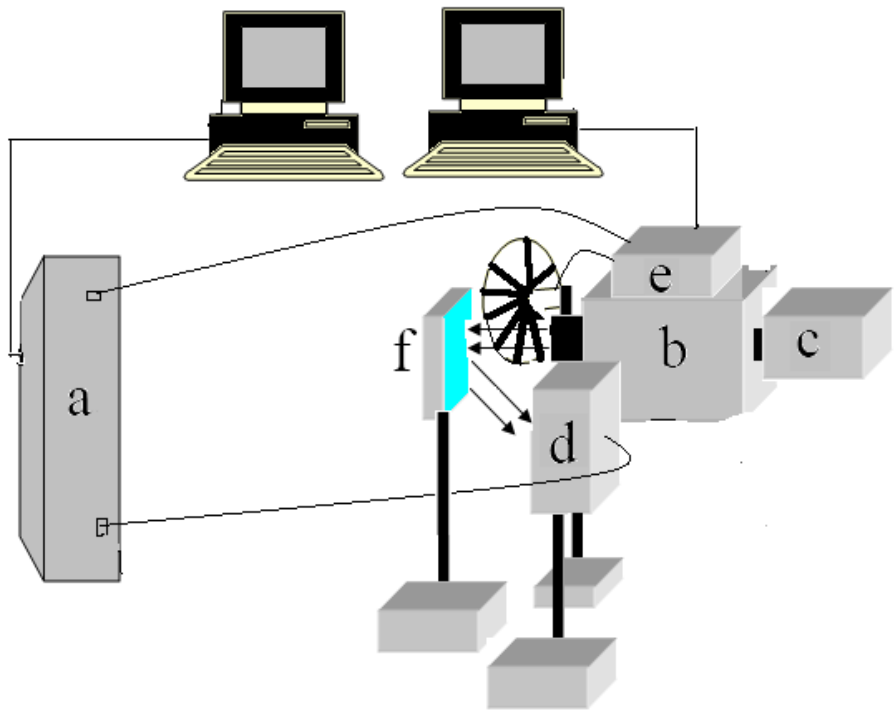

Figure 3.1: Reflectance measurement set up. (a) Lock-in-amplifier. (b) Monochromator. (c) Xenon arc lamp housing. (d) Detector. (e) Chopper control. (f) Sample(Polycrystalline silicon solar cell).

The monochromatic light from monochromator needs to be modulated and source of modulation must be available to lock-in-amplifier, to trigger the reference oscillator. Optical chopper (model SR540) with frequency set to be 856Hz used to chop the light before it fall on the sample. The chopped light fall on the sample at distance of 9.5cm from monochromator. A sample is a little bit shifted from it's normal to incoming light. The reflected light from sample directed to the detector which was placed at 6.5cm from the sample. The signal from the detector fed in to lock-in-amplifier (model SR830). The monochromator and lock-in-amplifier interfaced with individual personal computer and controlled by labVIEW program.

Incident power from the monochromator was also measured using the same set up. In this case the detector was placed normal to incident light at distance of 17cm from

monochromator. The labVIEW programs in the two computers that controls the lock-in-amplifier and monochromator set to run simultaneously and to reduce noise problem the laboratory was made to be dark as much as possible for all measurements.

3.2.2 Current density-voltage characteristics measurement

The current -voltage characteristics for both dark and under illumination were measured using CHI600A Electrochemical analyzer. This instrument controlled by external personal computer using it's own program chi600a. Linear sweep voltametry technique was chosen to linearly sweep voltage from -0.8V to 0.8V at interval of 0.001V. For under illumination measurement a 250W tungsten halogen lamp regulated by oriel power supply was used. The sample was placed in a sample holder and it was at 37cm on universal carrier (model 11622). The oriel power supply (model 661820) was set to be 90W, 6Amp, and 15V. for all illumination measurements. the set up for these measurements shown below.

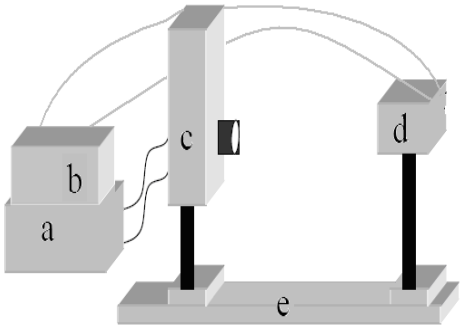

Figure 3.2: $J-V$ characteristics measurement set up. (a) Oriel power supply. (b) Electrochemical analyzer. (c) Quartz tungsten halogen lamp housing. (d) sample holder. (e) Universal carrier.

3.2.3 Short circuit current density with respect to wave length measurement

A sample at 37cm on universal carrier was illuminated with 250W tungsten halogen lamp regulated by an oriel power supply set at 90W, 6Amp and 15V. Monochromatic light was obtained with oriel grating with monochromator (model 77250) introduced in light path and scanned manually between 450nm and 800nm at interval of 10nm. CHI600A Electrochemical analyzer with bulk electrolysis technique was used to display the steady state current on computer. This current with it's respective wave length recorded manually after the sample illuminated for 10seconds at each selective wave length.

In the place of sample calibrating photodiode (Hamamatsu, model 5-1336-8BK) was placed and it's steady current for wave length 450nm to 800nm at interval of 10nm recorded manually. This for computing incident power for each wave length.

Irradiating the sample with ultraviolet ray was done using xenon arc lamp radiation source accompanied by filter that reject visible and infrared spectrum from radiation and allow ultraviolet ray to pass through it. The power supply for xenon arc lamp radiation source was fixed at 135W through out the experiment.

Each measurement discussed above were repeated after each UV exposure step. First a sample exposed for UV ray for 10minutes, then for 30, 60 and 90minutes.

Chapter 4

Result and Discussion

The amount of energy produced by PV device depends not only on available solar energy but how well the device, or solar cell converts sun light to useful electrical energy. this is called solar energy efficiency. It is solar cell conversion performance and depend on surface and electrical properties of solar cell. Effect of fluence of ultraviolet radiation on surface property (surface reflection) and electrical properties (current density-voltage characteristics and incident photon conversion efficiency) were investigated. The result of the measurements were presented and discussed in the following section.

4.1 The sample performance result before exposed to UV ray

4.1.1 Reflection measurement

Reflection measurement is optical method of gaining information about the surface of solar cell. Incident power to and reflected power from the sample were measured and using equation (2.3.2) reflectance spectrum of sample (polycrystalline silicon solar cell under investigation) in the region between 450nm to 1100nm plotted and shown below in figure (4.1).

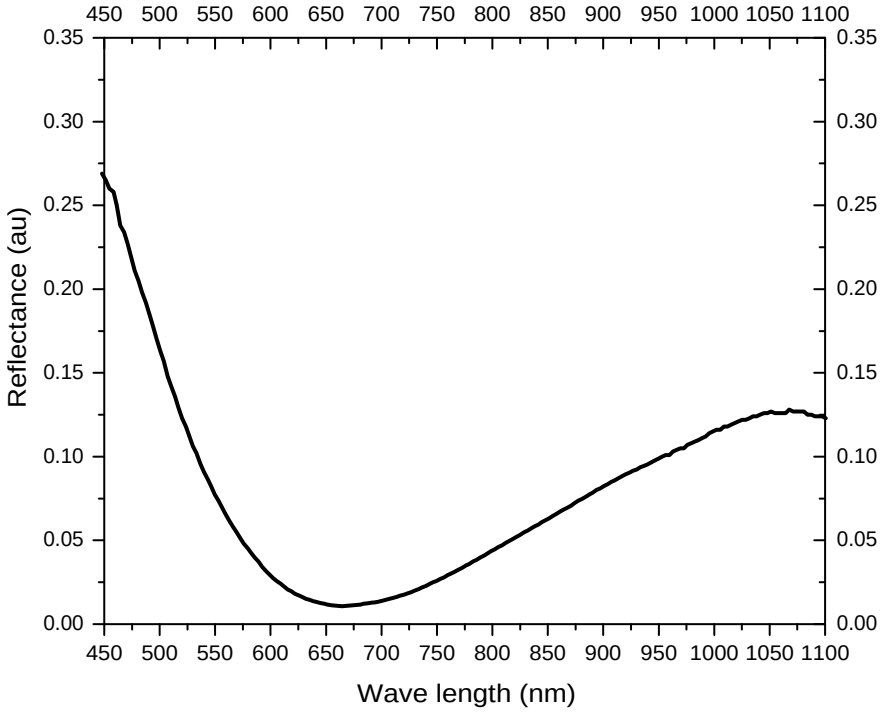

Figure 4.1: Reflectance spectrum of polycrystalline silicon solar cell

This spectrum shows total reflection is very much less than 30% of incident light,

that is a sample is not bare silicon[40]. It is coated with certain antireflection coating.

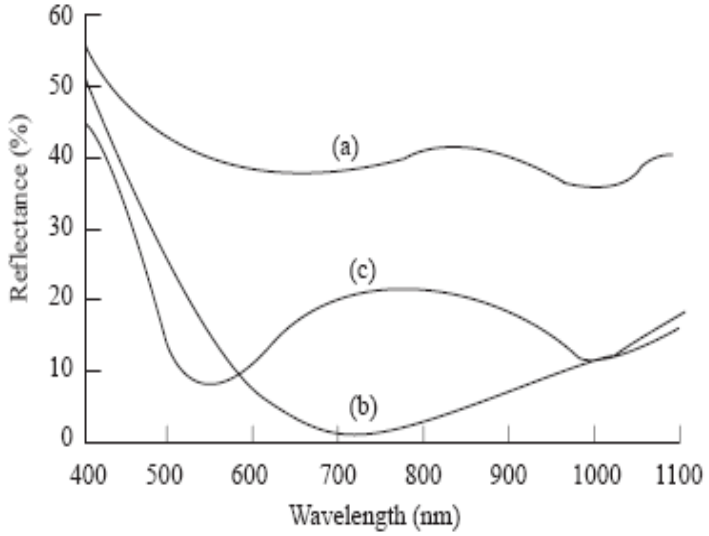

Figure 4.2: Reflectance spectrum of (a) an uncoated silicon surface,(b) a SiO single-layer (c) a $MgF_2 + SiO$ double-layer coating[41].

The reflectance spectrum of polycrystalline silicon solar cell under investigation shown in figure (4.1) is in a good agrement to a spectra of silicon solar cell coated with SiO shown figure (4.2).

4.1.2 The current density-voltage measurement

The current density-voltage measurement is fundamental electrical characterization technique used to solar cell performance evaluation[42]. the sample's current density-voltage characteristics shown in figure(4.3) and summarized in table(4.1).

$V_{oc}(V)$ $\pm$ $0.001V$	$J_{sc}(\frac{A}{cm^2})$	$P_{max}(W)\pm$ $0.001W$	$V_{max}(V)$	$J_{max}(\frac{A}{cm^2})$	$FF(\%)$ $\pm$ 0.1
0.504	0.037	0.011	0.397	0.029	62.1

Table 4.1: $J-V$ performance parameters extracted from figure(4.3).

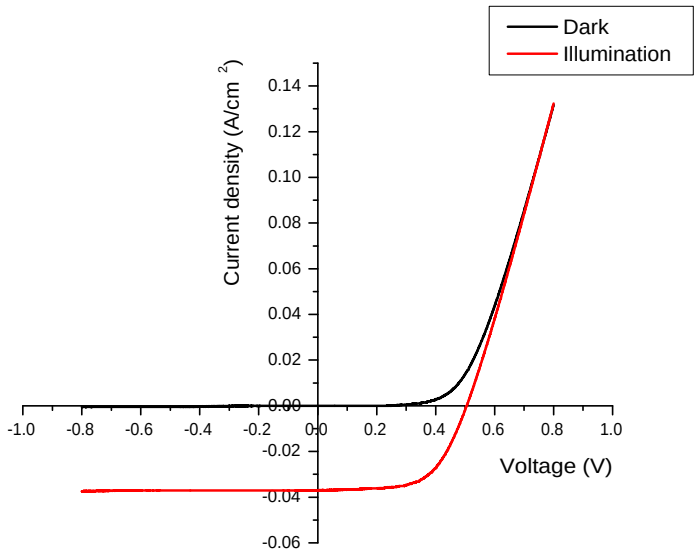

Figure 4.3: $J - V$ characteristics of polycrystalline silicon solar cell.

4.1.3 Incident photon conversion efficiency (External quantum efficiency)

It is measure of probability for incident photon at a given wave length to create electron-hole pair that will contribute to external current density of solar cell. External quantum efficiency (EQE) were plotted using equation (2.3.7) and it is similar to accepted EQE of silicon solar cell that is shown in figure (4.5) for the given wave length.

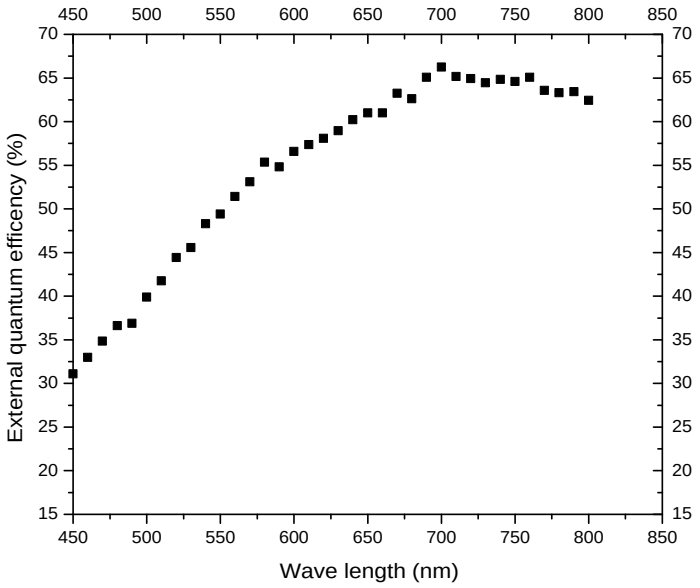

Figure 4.4: External quantum efficiency of polycrystalline silicon solar cell

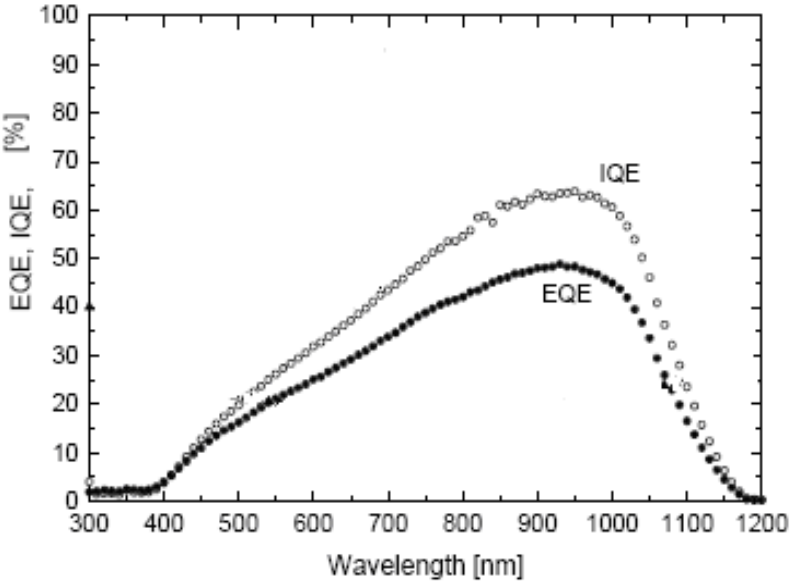

Figure 4.5: Quantum efficiencies of Si wafer substrate[43]

4.2 The sample performance result after different fluence of UV radiation

The ultraviolet radiation intensity was kept constant by keeping the power supply to UV source to a fixed point mentioned in the previous chapter. By varying exposure time of sample to UV radiation measurements were taken for different fluence of radiation and results presented below.

4.2.1 Reflection measurement

The reflectance spectra for different fluence presented below.

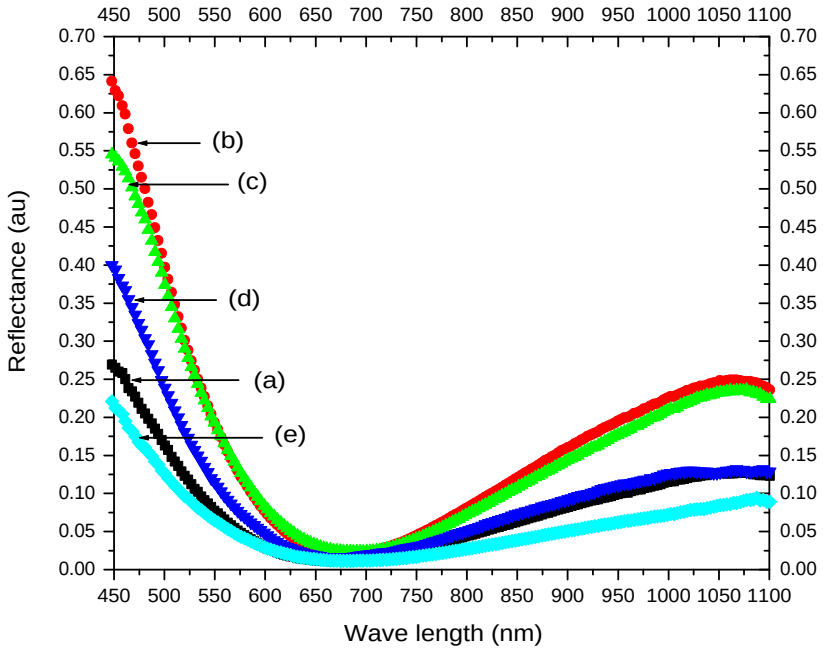

Figure 4.6: Reflectance spectrum of polycrystalline silicon solar cell. (a) before (b) after 10 minutes exposure (c) after 30 minutes exposure (d) after 60 minutes exposure (d) after 90 minutes exposure

UV radiation removes gases like Nitrites, Sulfites, Carbon monoxides and other Oxygen and Hydrogen compounds and particulate like mist, smog and dusts[44]. These impurities on the surface of solar cell absorb portion of incoming light before absorbed by the solar cell. For 10 minutes exposure reflectance spectrum increase due to decomposition and removal of gases and particulate by UV radiation. For additional 30 minutes and 60 minutes reflectance spectrum decreased compared to that of 10 minutes exposure. For 90 minutes exposure of UV radiation reflectance spectrum is more or less identical to that of before exposure shown in (a). Minimum of reflectance occurs from 665-680 nm and significant phase shift of spectrum is not seen.

4.2.2 The current density-voltage measurement

The current density-voltage characteristics for the sample after irradiated by different fluence of UV radiation shown in the following figures and summarized in table (4.2)

	$V_{oc}(V)\pm$ $0.001V$	$J_{sc}(\frac{A}{cm^2})$	$P_{max}(W)\pm$ $0.001W$	$V_{max}(V)$	$J_{max}(\frac{A}{cm^2})$	$FF(\%)\pm$ 0.1
Before exposure	0.504	0.037	0.011	0.397	0.029	62.1
10 minutes exposure	0.506	0.041	0.011	0.344	0.034	55.0
30 minutes exposure	0.489	0.037	0.010	0.312	0.033	55.5
60 minutes exposure	0.489	0.037	0.010	0.288	0.035	55.5
90 minutes exposure	0.489	0.040	0.010	0.280	0.036	52.6

Table 4.2: Performance parameters extracted from $J-V$ characteristics shown figure(4.7).

The reference performance parameters for this work is the parameters that is shown in table (4.1). The percentage deviation of respective parameter

$$\Delta\% = (\frac{parameter - reference\ parameter}{reference\ parameter})\ .\ 100\%$$

	$\Delta\%$					
	V_{oc}	J_{sc}	P_{max}	V_{max}	J_{max}	FF
10 minutes exposure	0.396	10.8	0.00	-13.3	17.2	-9.98
30 minutes exposure	-2.97	0.00	-9.09	-21.4	13.7	-9.16
60 minutes exposure	-2.97	0.00	-9.09	-27.4	20.6	-9.16
90 minutes exposure	-2.97	8.10	-9.09	-29.4	24.1	-13.9

Table 4.3: Percentage deviation of performance parameters

After 10 minutes of exposure open circuit voltage (V_{oc}) and maximum potential power (P_{max}) remain stable, short circuit current density (J_{sc}) and maximum current density (J_{max}) showed minimal increase. Short circuit current density is a function illumination intensity. After 10 minutes of exposure a solar cell receive better illumination. As exposure time increase for 30, 60 and 90 minutes nearly all parameters including fill factor remain stable.

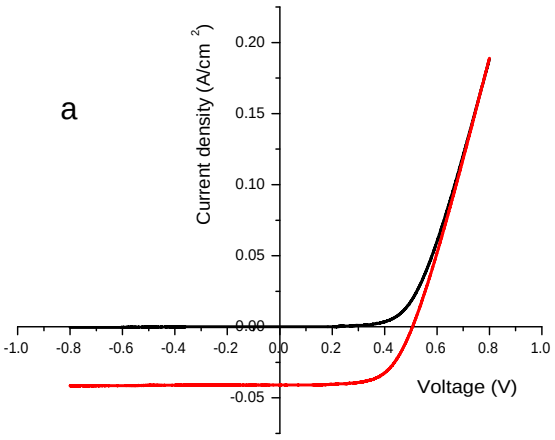

Figure 4.7: $J-V$ characteristics of polycrystalline silicon solar cell (a) for 10 minutes radiation

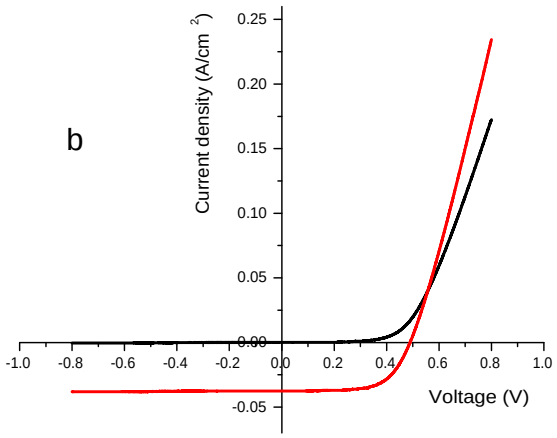

Figure 4.8: $J-V$ characteristics of polycrystalline silicon solar cell (b) for 30 minutes radiation

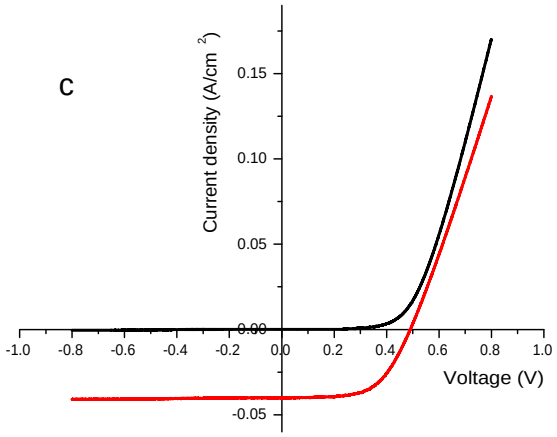

Figure 4.9: $J-V$ characteristics of polycrystalline silicon solar cell (c) for 60 minutes radiation

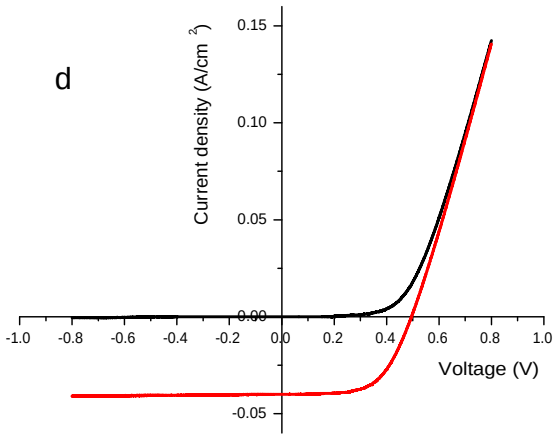

Figure 4.10: $J-V$ characteristics of polycrystalline silicon solar cell (d) for 90 minutes radiation

4.2.3 External quantum efficiency

The external quantum efficiency of analyzed solar cell before and after UV illumination is presented in figure (4.8). The peak of EQE for all fluences is 700 nm and for wave length 640-660 nm the EQE is independent fluence. From equation (2.3.9) and (2.3.10) the area under EQE plot told us information about spectral response of sample. The effect of increased front surface recombination rate affect the quantum efficiency of solar cell from 450-640 nm and beyond 660 nm.

	$Area(unit)^2$	$\Delta\%$
Before	192.17	—
10 minutes exposure	170.25	-11.4
30 minutes exposure	169.92	-11.5
60 minutes exposure	172.00	-10.4
90 minutes exposure	171.09	-10.9

Table 4.4: Comparison of the area under external quantum efficiency versus wave length for different fluence of UV radiation.

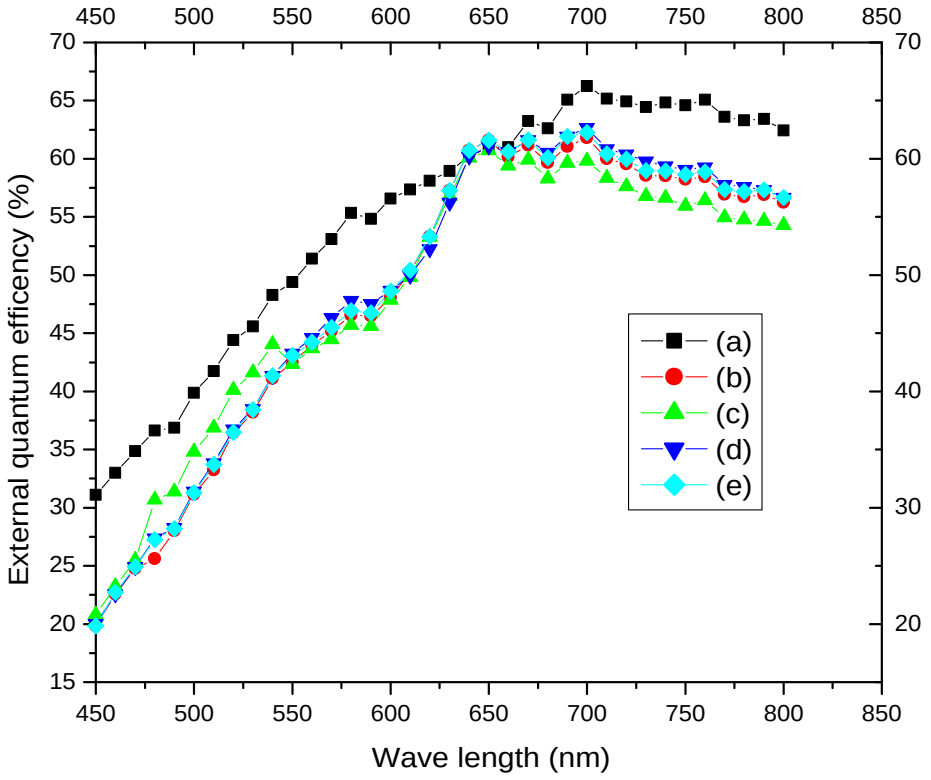

Figure 4.11: External quantum efficiency of polycrystalline silicon solar cell. (a) before (b) after 10 minutes exposure (c) after 30 minutes exposure (d) after 60 minutes exposure (e) after 90 minutes exposure

4.3 Conclusion

In this work effect of UV radiation on reflectance spectrum, performance parameters and external quantum efficiency of polycrystalline silicon solar cell was studied. UV radiation cleans the surface of a cell from gases and particulate that shade a cell from incoming light consequently reflectance spectrum have changed,however it comes to nearly original value after 190 minutes exposure. Most performance parameters and external quantum efficiency of a solar cell were stable after 10 minutes up to 190 minutes exposure to UV radiation. Further work has to be done by increasing exposure time for UV radiation to see the effect on performance parameters and reflectance spectrum of polycrystalline silicon solar cell.

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