Performance of Semiconductor Diodes Fabricated from Silicon and Carbon doped with Magnesium, Aluminium, Sulphur, Copper, Zinc and Cadmium

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DEDICATION

TO MY

MOTHER AMNA

AND

FATHER

AND TO

ALL MY FAMILY MEMBERS
Acknowledgements

All thanks to Prof Mubarak dirar Abd-Allah for his kind supervision and for the valuable time spent in helping, guiding and encouraging me to accomplish this work. Special thanks to Dr Mohammed Saeed Daw Elbeit, for his continuous help and guiding me during the period of all courses of the Diploma and Master and doing this work. My thanks extended to Dr Mustafa Ohag Mohamed for useful information in this work. Also thanks to Dr Asim Ahmed Mohamed. Thanks extend also to Mr. Abdel Sakhi Suleiman Hamid for helping in doing experimental work, in the Faculty of Science and Technology – Al Neelain University beside Mr. A. Elftah for his help during UV work and Ahmed Mohamed Elhaj for the help in printing this thesis. Finally my thanks extended to my friends.
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Abstract

The energy problem is one of the most long standing problems facing mankind. Different attempts were made to solve this problem, such as using solar cells which are considered as one of the most promising renewable energy sources. The available types of solar cells suffer from their low efficiencies and their high costs. The aim of this research is to study the performance of fabricated solar cells. By using chemical methods silicon was doped with Mg, Al, S, Cu, Zn and Cd. The current-voltage characteristics of the resulting fabricated p-n junction solar cells were studied. Also, the optical properties were studied using ultraviolet spectrophotometer. The results found showed that for doping silicon with Al, S and Cu having atomic numbers 13, 16 and 29 the efficiency values were found to be 0.0650, 0.0560 and 0.0090, respectively. The decrease of efficiency, here, with the increase of the atomic number may be related to the fact that the increase of atomic number increases the nuclear attraction to electrons thus decreasing their velocity and chance to scape which decreases the current and thus decreases efficiency. For Cu, Zn and Cd, with atomic numbers 29, 30 and 48 the efficiency increases and takes the values 0.0090, 0.0280 and 0.0651, respectively. In this case atoms may act as electric dipoles that may increase the internal deflection layer potential which increases the generation rate. When the host material is changed from silicon to carbon the efficiency decreases with increasing atomic number for Al, S, Zn, and Cd which have atomic numbers 13, 16, 30, and 48 respectively. The efficiency decreases and takes the values 0.440, 0.375, 0.020 and 0.019. For Mg, Al and Cu which have atomic numbers 12, 13 and 29, respectively, the efficiency increases with atomic number and takes the values 0.009, 0.440 and 1.3, respectively. The comparison of efficiencies of carbon and silicon shows increase of the efficiency of carbon in average compared to silicon. This may be related to the effect of energy gap on the efficiency, where the carbon gap is narrower than the silicon gap. Thus, it may be concluded that, changing the host
and keeping the same doping materials is unlikely to change the general features of the efficiency of a solar cell. This research recommends to repeat the study made here by changing the doping materials by other materials having similar outer most electronic configurations as the doping materials used here while keeping silicon and carbon as host materials. In this way it can be seen whether the general features of the efficiency found here are universal or a special case.
أداء دايد أشباه الموصلات المحضرة من تشوب السيليكون والكبريت والمغنازيوم

و الألوميوين والكربون والنحاس والزنك والكادميوم

قسم الله حسن حسن على

ملخص الدراسة

تعتبر معضلة الطاقة من أهم المعضلات التي تواجه الإنسان. كان من بين المحاولات لحل هذه المعضلة استعمال الخلايا الشمسية كأحد مصادر الطاقة المتجددة الواصلة. تعاني الخلايا الشمسية المتاحة حاليا من كفاءاتها المنخفضة وتكلفةتها العالية. هذه الأسباب جعلت هدف هذا البحث دراسة كفاءة أداء الخلايا الشمسية محورة. استعملت الطريقة الكيميائية لتشوب السيليكون بعناصر Mg, Al, S, Cu, Zn, Cd للخلايا الشمسية المحورة الناتجة. كانت دراسة الخواص البصرية لها - بواسطة مطياف الأشعة فوق البنفسجية ذات الأعداد الذرية 13, 16, 29.

بينت النتائج أن كفاءة الخلايا الشمسية الشموعية بعناصر Cu, S, Al هي 0.0650, 0,0090 على التوالي. يمكن أن يعزى انخفاض الكفاءة هنا مع زيادة العدد الذري للمادة الشموعية إلى أن زيادة العدد الذري يزيد من قوة جذب النواة للإلكترونات مما يقلل من سرعتها واحتمال خروجها من الذرة. هذا يؤدي إلى انخفاض كفاءة الأداء. بالنسبة للخلايا الشموعية بالعناصر Zn , Cu والتي أعدادها الذرية 29 , 30 و 48 على التوالي.

في هذه الحالة احتل السيليكون كأضلاع كثيرة تزيد من الجهد الداخلي الحارف والذي يزيد من معدل التوليد. عندما بدلت مادة السيليكون المضيفة بمادة الكربون تتضمن الكفاءة زيادة معدل الذري للعناصر Cd, Zn, S, Al والتي أعدادها الذرية 30, 16, 13, 48 على التوالي تتضمن الكفاءة لتأخذ القيم 0.028, 0.065, 0.028, 0.009 على التوالي.

وتوضح مقارنة كفاءة الكربون مع السيليكون زيادة متوسط كفاءة الكربون مقارنة مع السيليكون وها قد تعزى لتأثير ضعف الطاقة على الكفاءة حيث أن فجوة الكربون أضيف من فجوة السيليكون. عليه يمكن الاستنتاج أن تغيير العنصر المضيف مع استعمال نفس المشبوطات لا يغير الملامح العامة للكفاءة الخلايا الشمسية. يوصي هذا البحث بإعادة الدراسة التي تمها بابدال العناصر المشبوهة بعناصر أخرى ذات بنية إلكترونية خارجية مشابهة تتعلق بسلوك المشابات المستعملة هنا مع إبقاء السيليكون وكربون كعناصر مضيفة - حيث يمكن معرفة عما إذا كانت معالم كفاءة أداء الخلايا الشمسية المحورة المتحصل عليها في هذا البحث ملامح أساسية عامة أم هي حالة خاصة.
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Chapter One

Introduction

1.1 General Introduction

Throughout the entire modern age, mankind has used fossil fuels to meet its energy requirements. Coal, oil and natural gas have lit homes and powered machinery for centuries, driving civilization forward. But as human development accelerated, the unsustainability of such energy became apparent. Global fuel supplies deteriorated and the atmosphere became more polluted. The search for renewable sources of energy began, to ensure a sustainable future. Today, our civilization stands at a critical juncture. We are on the cusp of adopting clean energy at a scale never seen before. But for renewable power to continue its rapid advancement, the right decisions need to be taken. When clean energy first made headway in the global scenario, questions were raised about how stable and scalable it was. At a macro level, unstable policies for powering future growth were exacerbated by technological immaturity and lack of funding. Nevertheless, clean energy installations continued to grow, albeit slowly, until a dramatic leap a few years ago. Today, a fifth of the world’s electricity is produced by renewable energy. In 2016, there were 160GW of clean energy installations globally. This is 10% more than in 2015, but they cost almost a quarter less. New solar power gave the biggest boost, providing half of all new capacity, followed by wind power, which provided a third, and hydropower, which gave 15% it was the first year in history that added solar capacity outstripped any other electricity-producing technology. Steady increase in energy consumption is one of the main challenges our society faces today (Tulsi, 2018). The available sources of energy can be broadly divided into two big categories: renewable and non-renewable. For a stable development of human civilization in a long run only renewable energy sources, such as wind, water, wave, tide, geothermal and solar, with the smallest impact upon environment, can be considered as a viable option. Even though nuclear energy has been a consistent source of energy for a very long period, doubts have been raised about its continuation after the last year’s Japan disaster. The Earth receives an incredible supply of solar energy. The sun, an average star, is a
fusion reactor that has been burning over 4 billion years. It provides enough energy in one minute to supply the world's energy needs for one year. In one day, it provides more energy than our current population would consume in 27 years. In fact, the amount of solar radiation striking the earth over a three-day period is equivalent to the energy stored in all fossil energy sources. Solar energy has broad range of applications ranging from lighting, heating, distillation and production of fuels. Generation of electricity from solar energy which is considered free, inexhaustible resource, yet harnessing it is a relatively new idea. Motivated by continuously growing global energy demands and the depletion of readily accessible fossil fuels; the search for alternative energy sources, particularly renewable solar energy, has become vital. Despite the clear advantages associated with the adoption of solar cells, they need to be cost-effective and priced competitively in comparison to conventional energy resources, as any technological or performance improvements must be balanced against the associated cost (Chaar et al., 2011). The greatest advantage of solar energy compared with other forms of energy is that it is clean and can be supplied without environmental pollution. (Hino et al., 2006; Hoke et al., 2013). Over the past century, fossil fuels provided most of our energy, because these were much cheaper and more convenient than energy from alternative energy sources, wherefore was used Sunlight which can be converted into electricity using photovoltaic (PV) . A solar cell is a device that converts light into direct current using the photoelectric effect.

1.2 Research Problem

Solar energy is currently dominated by the single-crystalline silicon cell, which occupies as much as 90% total photovoltaic cells and the silicon is nontoxic and is second only to oxygen in the earth's crust. However, there are still a lot of issues related to wafer-Si solar cells such as high manufacturing cost, recombination, reflection and absorption losses along with efficiency issues in multi-crystalline and amorphous silicon based cells due to their disordered nature. In order to use the photovoltaic effect to its highest potential, it is important to find either the solution to the problems associated with silicon or other materials which can implement the photovoltaic effect in exclusive and cheaper ways. Also solar cells fabricated from silicon are widely used now, but unfortunately its
fabrication is complex and expensive. This forces scientists to search for alternative cheap materials that can be used to fabricate solar cells easily. There are many alternatives for silicon, among which using dyes to fabricate dye solar cells or polymers to fabricate polymers solar cells. In spite of fact that the manufacturing cost of these types of solar cells is lower, but their efficiencies are lower in comparison with silicon solar cells. Using materials in thin films instead of the materials in bulk is another way to lower the cost. But the electrical and optical properties of the materials used in fabrication of solar cells are of great importance.

1.3 Thesis Objective

The objective of this thesis is to fabricate silicon and carbon solar cells where silicon and carbon are used as host materials, using chemical methods. The dopant materials are (Mg, Al, S, Zn, Cu and Cd). And to study the performance of the resulting fabricated solar cells.

1.4 Thesis layout

This thesis is divided into five chapters. First, chapter one is the introduction to the work where problem statement, objectives and scope of research are presented in this chapter. Chapter two describes the types of semiconductors and the electrical and optical properties of semiconductors and p-n junction formation and biased reverse biased p-n junction diode. Also p-n junction diodes which act as solar cells fabricated from certain materials are exhibited. The basic principle of solar cell operation is studied and their performance is also studied in this chapter. Types of solar cells, the four generations of solar cells and the physical and chemical properties of the materials used in fabrication the solar cell are studied in this chapter. This chapter ends with the previous studies related to the work. Chapter 3 describes the methodology used in the design of the experiments the experimental procedures and materials used are included in this chapter. While chapter 4, presents the experimental results together with their analysis and discussion. Chapter 5 summarizes the main conclusion of the thesis and presents recommendations.
Chapter two

Literature review

2.1 Introduction

Semiconductor materials are the backbone of modern electronic industry, which is based on the fabrication of semiconductor devices. This industry is based on the production of computers, cell phones, light emitting diodes (LED), photodiodes, laser diodes, detectors, solar cells and others from different semiconductor materials. A semiconductor is usually defined as a material with electrical resistivity lying in the range of $10^{-2}$ - $10^{9} \Omega \cdot cm$. Alternatively, it can be defined as a material whose energy gap for electronic excitations lies between zero and about 4 electron volt (eV) (Peter, 2003). Material with zero band gap are metals or semimetals. The band gap of insulators is usually on the order of 3.5 to 6 eV or larger. (Neaman, 2003).

Semiconductors occur in many different chemical compositions with a large variety of crystal structures. They can be elementals or compounds. Elemental semiconductors such as silicon (Si), carbon (C), germanium (Ge) and selenium (Se). These elements belong to group IV of the periodic table of elements. Compound semiconductors can be binary, ternary or quaternary compounds. The binary compounds are formed from elements of group II and VI, (II- VI) compounds such as zinc oxide ZnO, zinc sulfide ZnS, cadmium sulfide CdS. The ternary compounds are formed from elements of (III) and (V) such as Gallium arsenide GaAs and AlAs aluminum arsenide. Quaternary compounds take the form $A_x B_{1-x} C_y D_{1-y}$ can be obtained from combination of many binary and ternary compound semiconductors. For example, GaP, InP, InAs, plus GaAs can be combined to yield the alloy semiconductor $Ga_x In_{1-x} As_y P_{1-y}$ There are some oxides exhibiting semiconducting properties such as CuO and Cu$_2$O.
2.2 Colors of semiconductors

The color of absorbed and emitted light both depend on the band gap of semiconductor. Visible light covers the range of approximately 390-700 nm, or 1.8-3.1 eV. The color of absorbed light includes the band gap energy, but also all colors of higher energy (shorter wavelength), because electrons can be excited from the valence band to a range of energies in the conduction band. Thus semiconductors with band gaps in the infrared (e.g., Si, 1.1 eV and GaAs, 1.4 eV) appear black because they absorb all colors of visible light. Wide band gap semiconductors such as TiO$_2$ (3.0 eV) are white because they absorb only in the UV. Fe$_2$O$_3$ has a band gap of 2.2 eV and thus absorbs light with $\lambda < 560$ nm. It thus appears reddish-orange (the colors of light reflected from Fe$_2$O$_3$) because it absorbs yellow, green, blue, and violet light. Similarly, CdS ($E_{\text{gap}} = 2.6$ eV) is yellow because it absorbs blue and violet light. The band gap is a very important property of a semiconductor because it determines...
its color and conductivity. Many of the applications of semiconductors are related to band gaps: Narrow gap materials (Hg$_x$Cd$_{1-x}$Te, VO$_2$, InSb, Bi$_2$Te$_3$) are used as infrared photodetectors and thermoelectrics (which convert heat to electricity). Wider gap materials (Si, GaAs, GaP, GaN, CdTe, CuIn$_x$Ga$_{1-x}$Se$_2$) are used in electronics, light-emitting diodes, and solar cells.

### 2.3 Doping semiconductors

Doping a semiconductor means incorporation of foreign impurities to a pure semiconductor (intrinsic) for the purpose of increasing its electrical conductivity. The doped one is called extrinsic. At low temperatures intrinsic semiconductor may become a perfect electrical insulator since its valence band is totally filled with valence electrons and the conduction band is completely empty. However as the temperature rises, the concentration of holes or electrons increases. Equation (2.1) shows that the intrinsic carrier concentration is temperature and band gap dependent.

$$ n_i = B T^{3/2} \exp \left( \frac{-E_g}{k_B T} \right) $$

(2.1)

Where $T$ is temperature, $E_g$ is the band gap energy, $B$ is a coefficient related to the specific semiconductor material and $k_B$ is Boltzmann’s constant. (Fonstad, 2006). If doping concentration becomes significantly high, the material starts behaving more like a conductor and it becomes a degenerate semiconductor. (Figueroa, 2012) Because of the expansion and contraction of the lattice with temperature, the various band parameters, particularly the energy gap is temperature dependent.

#### 2.3.1 N-type doping

When a trace amount of element from group VI (like phosphorus P or Arsenic As) is introduced in Silicon (Si) and since silicon has four valence electrons and arsenic or phosphorus has five valence electrons, the later form four bonds by sharing four electrons with neighboring silicon atoms. The thermal energy of the crystal at room temperature is large enough to remove the loosely held fifth electron from the phosphorus
outer electronic shell and reside in the conduction band where it is free to move in the crystal. The phosphorus atoms in silicon are called donor atoms.

Figure (2.2)  N- Doping silicon with phosphorus. (Razeghi, 2002)

A semiconductor containing donor impurity atoms is called n-type in which electrons are the majority carriers and holes are the minority carriers.

2.3.2 P-type doping

When substituting an atom from group (IV) like silicon with an atom from group (III) like Galium (Ga) or Boron (B), this results in a missing electron. This is shown in Figure (2.3). The Galium atom can easily capture an electron to form a fourth bond with silicon atoms, thereby creating an immobile negatively charged Galium atom. This releases a hole in the crystal, located in the valence band. This hole can move about in the crystal, thereby participating in electrical conduction. The Galium atom in silicon is
called acceptor. A semiconductor containing an acceptor impurity is called p-type in which holes are the majority carriers and electrons are the minority carriers.

![Diagram of P-type doping with gallium](image)

**Figure (2.3) P-type doping silicon with gallium. (Razeghi, 2002)**

Sometimes it is not immediately obvious what kind of doping (n- or p-type) is induced by messing up a semiconductor crystal lattice. In addition to substitution of impurity atoms on normal lattice sites, it is also possible to dope with vacancies - missing atoms - and with interstitials - extra atoms on sites that are not ordinarily occupied. Some simple rules are as follows:

1. For substitutions, adding an atom to the right in the periodic table results in n-type doping, and an atom to the left in p-type doping.
2. Anion vacancies result in n-type doping, and cation vacancies in p-type doping.
3. Interstitial cations (e.g. Li) donate electrons to the lattice resulting in n-type doping.
Interstitial anions are rather rare but would result in p-type doping. Sometimes, there can be both p- and n-type dopants in the same crystal, for example B and P impurities in a Si lattice, or cation and anion vacancies in a metal oxide lattice. In this case, the two kinds of doping compensate each other, and the doping type is determined by the one that is in higher concentration. A dopant can also be present on more than one site. For example, Si can occupy both the Ga and As sites in GaAs, and the two substitutions compensate each other. Si has a slight preference for the Ga site, however, resulting in n-type doping.

### 2.4 Fermi level

The probability that an electronic state of energy E and temperature T is occupied by an electron is given by the Fermi – Dirac distribution function \( f(E) \)

\[
f(E) = \frac{1}{1 + e^{\frac{E-E_f}{K_B T}}}
\]  

(2.2)

Where \( E_f \) is Fermi energy level, \( K_B \) Boltzmann’s constant. Fermi energy represents the value of energy where all states below which are occupied and all states above are empty at absolute temperature \( T = 0 \) Kelvin. Alternatively the Fermi for intrinsic semiconductors can be defined as the value of energy where the probability of a state being occupied is 0.5 at any temperature T. The probability of state being occupied \( f(E) \) vs. energy E is shown in Figure (2.4)
In the case of intrinsic material, the Fermi level is located in the middle of the band gap whereas it is located near the conduction band for an n-type semiconductor and near the valence band for p-type semiconductor as is plotted in Figure (2.5) with the probability of occupation.

**Figure (2.5)** The position of Fermi level with respect to conduction and valence bands and Fermi functions

### 2.5 Carrier concentrations

Any operation of a semiconductor device depends on the concentration of carriers that transport charge inside the semiconductor and hence cause electrical currents. Knowledge of the concentration of carriers under equilibrium or unperturbed state of a system, to which no external voltage, magnetic field, illumination, mechanical stress, or other perturbing forces are applied to a device, leads to Knowledge of the principle of operation of that device. The total concentration of electrons in the conduction band and the total concentration of holes in the valence band is obtained by multiplying density
of states function with the distribution function and integrating across the whole energy band and is given by equation (2.3) and (2.4)

\[ n_o = N_c e^{\frac{E_c - E_f}{k_BT}} \quad (2.3) \]
\[ p_o = N_v e^{\frac{E_f - E_v}{k_BT}} \quad (2.4) \]

Where \( N_c \) and \( N_v \) are the effective density of states of electrons in the conduction band and holes in the valence band, respectively. \( n_o, p_o \) are the equilibrium carrier concentration of electrons and holes in the conduction band and valence band, respectively. For intrinsic semiconductor, \( n_o = p_o = n_i \) and from equation (2.3) and (2.4)

\[ n_o p_o = n_i^2 \quad (2.5) \]
\[ n_i = \sqrt{N_c N_v} e^{\frac{E_g}{2k_BT}} \quad (2.6) \]

Equation (2.3) and (2.4) can be written in the form

\[ n_o = n_i e^{\frac{E_i - E_f}{k_BT}} \quad (2.7) \]
\[ p_o = n_i e^{\frac{E_f - E_i}{k_BT}} \quad (2.8) \]

Equation (2.7), (2.8) show that, when the concentration of dopant increases, the Fermi level will shift. This shift will be to the conduction band for an n-type semiconductor and to the valence band for a p-type semiconductor. For degenerate semiconductor the Fermi levels are outside the energy band gap.

The conductivity of a semiconductor material \( \sigma \) is directly related to the number of conduction electrons and holes as given by equation (2.9)

\[ \sigma = q \left( n \mu_n + p \mu_p \right) \quad (2.9) \]

where \( q \) is the electronic charge, \( n \) is the number of conduction electrons, \( p \) is the concentration of holes and \( \mu_n, \mu_p \) are electron and hole mobilities. When a semiconductor is illuminated by light source to create electron-hole pair, its conductivity
increases. Photoconductivity gives very useful information on the performance of solar cell.

2.6 Determination of Band Gaps

When matter interact with radiation the following processes may occur, absorption and emission, the latter is either spontaneous or stimulated emission. When a photon with energy \( E = h\nu > E_g \) is absorbed by an electron of energy \( E_1 \) in the valence band its energy will become \( E_2 \) in the conduction band such that

\[
h\nu = E_2 - E_1 \tag{2.10}
\]

\[
E_2 = E_c + \frac{(hk)^2}{2m_e} \tag{2.11}
\]

\[
E_1 = E_v - \frac{(hk)^2}{2m_v} \tag{2.12}
\]

Substituting equation (2.11) and (2.12) in (2.10) and knowing that \( E_c - E_v = E_g \)

\[
h\nu = E_g + \frac{(hk)^2}{2m_r} \tag{2.13}
\]

where \( m_r \) is the reduced mass. Substituting the value of \( k \) in equation (2.13) in (2.11) and (2.12)

\[
\rho_c (E_2) \, dE_2 = \rho(v)dv
\]

where \( \rho(v) \) is the optical join density of states of electrons in the conduction band, which is the number of states per unit volume for photons of energy between \( h\nu \) and \( h(v + dv) \) to interact with.

\[
\rho (v) = \frac{1}{\pi h^2} \sqrt{\frac{2m_r}{(h\nu - E_g)^2}} \tag{2.14}
\]

The probabilities of emission \( P_e \) and absorption \( P_a \) can be given by

\[
P_e = f(E_2)[1 - f(E_1)] \tag{2.15}
\]

\[
P_a = f(E_1)[1 - f(E_2)] \tag{2.16}
\]

where \( f(E_2) \) represents the probability of occupation of electron in the conduction band, \( [1 - f(E_2)] \) represents the probability of occupation of hole in the valence band. In thermal equilibrium only one Fermi function to represent the occupation probabilities in the valence and conduction bands, \( P_a >> P_e \)

whereas in quasi equilibrium there are two Fermi functions.
For \( P_e(\nu) > P_a(\nu) \rightarrow (E_{fc} - E_{fv}) > E_g \); the difference between quasi Fermi levels is greater than the band gap, this is the condition for semiconductor laser.

The gain coefficient \( \gamma \) is given by

\[
\gamma = \frac{(c/n)^2}{8\pi^2 \tau} \rho(\nu)[f_e(\nu) - f_a(\nu)]
\]

(2.17)

where \( c \) is the velocity of light in vacuum, \( n \) is refractive index of the semiconductor material through which light waves propagate, \( f_e(\nu), f_a(\nu) \) are the probability of emission and absorption, respectively.

In the case of semiconductor laser, the gain coefficient \( \gamma > 0 \)

For \( P_e(\nu) < P_a(\nu) \rightarrow (E_{fc} - E_{fv}) < E_g \); the difference between quasi Fermi levels is less than the band gap, the gain coefficient \( \gamma < 0 \) there is loss or attenuation.

### 2.7 Absorption of photons

For solar cells, the generation of electrons and holes by the absorption of photons is the most important process. The probability for the absorption of photon of energy \( (\hbar \omega) \) is defined by the absorption coefficient \( \alpha(\hbar \omega) \), which is a material property and it is proportional to the density of occupied state in the valence band and unoccupied state in the conduction band. For direct band semiconductors, the absorption coefficient is given by

\[
\alpha(\hbar \omega) = A(\hbar \omega - E_g)^{\frac{1}{2}}
\]

(2.18)

where \( A \) is a constant. Photons with energy \( \hbar \omega < E_g \) can not be absorbed, photons of this energy are either reflected or transmitted. For indirect band semiconductors, the absorption coefficient is given by

\[
\alpha(\hbar \omega) = B(\hbar \omega - E_g \pm \hbar \Omega)^2
\]

(2.19)

where \( B \) is a constant. The plus sign for simultaneous absorption of photon and phonon and the minus sign for the emission of phonon with the absorption of photon. When light of intensity \( I_0 \) is incident on a semiconductor material, the transmitted intensity follows Lambert-Baer’s Law
The quantity $1/\alpha$ is known as the optical penetration depth. When the photon energy is increased from below to above the band gap, typically the semiconductor absorption coefficient increases rapidly to values as large as or larger than $10^4 \text{ cm}^{-1}$. As a result the sample becomes opaque for photon energies higher than the band gap unless its thickness is very small. Direct band gap semiconductors have high absorption coefficient, have low penetration depth like GaAs, for solar cell their thickness is only a few $\mu$m. For indirect band gap semiconductors the absorption coefficient is small so that the penetration depth is high. Therefore for silicon solar cell to absorb all photons with energy greater than the band gap it must be more than $100 \mu$m thick. (Wuerfel, 2005).

When a flux of photons is incident in a semiconductor material, the reflected, transmitted and absorbed photons, follow the relation: \[ I_0 = I_T + I_A + I_R \] as depicted in Figure (2.6)

Where $I_T$, $I_A$, and $I_R$ are the fraction of power that is transmitted, absorbed and reflected, respectively. Or, \[ \frac{I_T}{I_0} + \frac{I_A}{I_0} + \frac{I_R}{I_0} = T + A + R = 1 \] (2.21)

Where $T$, $A$ and $R$ are transmission, absorption and reflection coefficients, respectively. The absorption coefficient is also denoted by $\alpha(\omega)$ . Materials with little absorption and reflection are transparent, one can see through them. Materials in which light is transmitted diffusely are translucent. In Figure (2.6) light of intensity $I_0$ is incident on a medium, part of it reflected and another part is transmitted and the remainder is absorbed. If the medium is the active layer of a solar cell, the reflected and transmitted parts must be reduced for higher performance of the solar cell.
The optical absorption coefficient $\alpha(\omega)$, in a medium is defined as

$$\alpha(\omega) = \frac{\text{number of photons absorbed per unit volume per second}}{\text{number of photons injected per unit area per second}}$$

(2.22)

The absorption coefficient is wavelength dependent and it is given by

$$\alpha(\omega) = \frac{4\pi K(\omega)}{\lambda} = \frac{2\omega k(\omega)}{c}$$

(2.23)

where $c$ is the velocity of light in vacuum, $K(\omega)$ is the extinction coefficient, also known as the attenuation index. The reflection coefficient, $R(\omega)$, of a wave impinging on a medium characterized by real refractive index $n(\omega)$, and extinction coefficient $K(\omega)$, $i = \sqrt{-1}$

$$n_i = n(\omega) + iK(\omega)$$

(2.24)

The real refractive index $n(\omega) = \frac{c}{v}$

(2.25)

where $v$ is the velocity of light in the medium.

For normal incidence the reflectivity

$$R = \frac{(n-1)^2 + K^2}{(n+1)^2 + K^2}$$

(2.26)

For totally transparent material $K = 0$

light incident on a medium can be trapped by total internal reflection if the angle of incidence is greater than the critical angle $\theta_c$

$$\theta_c = \sin^{-1} \frac{n_1}{n_2}$$

(2.27)
where $n_2 > n_1$, in this case the probability that photons are being absorbed by the medium is increased.

**2.8 Recombination in Semiconductor**

The excess charge carriers created in a semiconductor by absorption of light are annihilated after the source light is turned off. This process is called recombination. The recombination phenomena in bulk is classified into direct recombination, indirect recombination via localized energy states in the forbidden energy gap and Auger recombination, these are depicted in Fig (2.7)

Fig (2.7) Recombination processes in semiconductors: (a) direct recombination, (b) Indirect and (c) Auger recombination.

In direct recombination, which usually dominates in direct band gap semiconductors, when an electron makes a transition from the conduction to the valence band, an electron-hole pair is annihilated, resulting in the emission of photon. Under thermal equilibrium conditions, the recombination rate is $\beta n_{n0} p_{n0}$ for an n-type semiconductor and is equal to the generation rate (the number of electron–hole pairs generated per unit volume per unit time) by thermal vibration, where $\beta$ is the proportionality constant and $n_{n0}$ and $p_{n0}$ are electron and hole concentrations, respectively, in n-type semiconductor at thermal equilibrium. When excess carriers are introduced by light illumination, the recombination rate is increased to $\beta n p$ because the recombination is proportional to the number of electrons in conduction band and that of holes is valence band. In the case of low-injection level, the net recombination rate is given by

$$U = \beta np - \beta n_{n0}p_{n0} = \beta (n_{n0} + \Delta n)(p_{n0} + \Delta p) - \beta n_{n0}p_{n0}$$
where \( \Delta n \) and \( \Delta p \) are the excess electron and hole concentrations by light illumination, \( \tau_p \) is the minority carrier (hole) lifetime. Similarly, in the case of p-type semiconductor, the net recombination rate is expressed as:

\[
U = \frac{\Delta n}{\tau_n}
\]

And the minority carrier (electron) lifetime expressed as:

\[
\tau_n = \frac{1}{\beta_{p0}}
\]

In case a semiconductor containing trap states near the midgap (Fig.2.7.b) with a concentration of \( N_t \), indirect recombination occur. This indirect recombination is very likely to be for indirect band gap semiconductor. For an n-type semiconductor, the minority carrier lifetime \( \tau_p \) the net recombination is given by:

\[
\tau_p = \frac{1}{v_{th} \sigma_p N_t}
\]

where \( v_{th} \) is the mean thermal velocity of hole and \( \sigma_p \) the capture cross section of the hole trap. Similarly, for a p-type semiconductor, the minority carrier lifetime is given by:

\[
\tau_n = \frac{1}{v_{th} \sigma_n N_t}
\]

In Auger recombination (Fig.2.7.c) one electron gives up its extra energy to another electron in the conduction band or the valance band during the recombination, resulting in the excitation of an electron to a higher energy level. The excited electron will give up this excess energy as heat when the excited electron relaxes to the band edge. Because the Auger process involves three particles, its recombination rate is expressed as:

\[
U = A n^2 p
\]

or

\[
U = A p^2 n
\]

For electron–electron–hole process and hole–hole–electron process, respectively. \( A \) is the Auger constant which strongly depends on temperature. Auger process is important when the carrier concentration is high, especially in low band gap semiconductor. Because a semiconductor is abruptly terminated, the disruption of the
periodic potential function results in the energy states within the energy band gap at the surface. These states – surface states – enhance the recombination near the surface. They become very important with reducing the crystal size because the number of carriers recombining at the surface per unit volume is increased. For a low-injection condition, the total number of carriers recombining at the surface per unit area and unit time is expressed as:

$$U_s = S(p_s - p_{n0})$$  \hspace{1cm} (2.36)

For an n-type semiconductor, where $S$ is the surface recombination velocity and $p_s$ is the hole concentration at the surface. When an n-type semiconductor is irradiated uniformly by the light to create excess carriers, the gradient of hole concentration yields a diffusion current, which is equal to the surface recombination current as shown in the following equation:

$$qD_p \frac{dp_n}{dx} \bigg|_{x=0} = qU_s = qS(p_s - p_{n0})$$  \hspace{1cm} (2.37)

### 2.9 Carrier transport

The net flow of the electrons and holes in a semiconductor will generate currents. The process by which these charged particles move is called transport. In addition to generation and recombination currents, there are two basic transport mechanisms in a semiconductor crystal: drift (the movement of charge due to electric fields), and diffusion (the flow of charge due to density gradients). In the real semiconductor, all the processes occur simultaneously, not individually. So all the components of the currents is governed by the continuity equation

$$\frac{\partial n_p}{\partial t} Adx = \left[ \frac{J_n(x)A}{-q} - \frac{J_n(x+dx)A}{-q} \right] + (G_n - R_n)Adx$$  \hspace{1cm} (2.38)

Where $A$ is the area of a slice of a semiconductor of thickness $dx$, $Adx$ is its volume (V) $G_n$, $R_n$ are the generation rate and the recombination rate of electrons, respectively. Using the Taylor series, for electrons in p-type semiconductor, the equation (2.38) can be written in the form

$$\frac{\partial n_p}{\partial t} = \frac{1}{q} \frac{\partial J_n}{\partial x} + (G_n - R_n)$$  \hspace{1cm} (2.39)

Similarly for holes in n-type semiconductor

$$\frac{\partial p_n}{\partial t} = \frac{1}{q} \frac{\partial J_p}{\partial x} + (G_p - R_p)$$  \hspace{1cm} (2.40)
The electric current density ($J$) for each type of carrier is the sum of drift and diffusion currents.

For electrons

$$J_n = qn \mu_n E + qD_n \frac{dn}{dx}$$

(2.41)

For holes

$$J_p = qp \mu_p E + qD_p \frac{dp}{dx}$$

(2.42)

At steady state condition $\frac{dn_p}{dt} = \frac{dp_n}{dt} = 0$

(Soga, 2006; Pierret, 1987; Fonstad, 2006)

### 2.10 p-n junction

A p-n junction consists of two semiconductor regions of opposite type, in contact to each other. P-n junctions are of great importance, both in modern electronic applications and in understanding other semiconductor devices. Depending on the doping profile, the materials used for fabrication, device geometry and biasing condition, a p-n junction can perform various terminal functions. (Sze, 2007). A semiconductor diode is simply a p-n junction, which can serve in electronics as rectifier, voltage regulator (zener diode), logic gate, switching or tuner (varactor diode) and in optoelectronic as light emitting diode (LED), laser diode, photodetector or solar cell. (Kuphaldt, 2009).

In the present research, the p-n junction is used as a solar cell.

#### 2.10.1 p-n junction diode in equilibrium

When a p-type and n-type semiconductors are brought in contact to form a junction, assuming uniformly doping (abrupt junction), there would be a rearrangement of mobile carriers. Since the concentration of electrons is greater in n region than in the p-region, electrons diffuse from the region of high concentration to the region of low concentration leaving behind positively charged ionized donor atoms. In the p-region the electrons recombine with the abundant holes. Similarly, holes diffuse from the p-region to the n-region, leaving behind negatively charged ionized acceptor atoms. In this region holes recombine with the abundant electrons.
As a result a narrow region on both sides of the junction becomes nearly depleted of charge carrier, this region is called depletion layer or space charge region (SCR). The diffusion of charge carrier result in diffusion current of electrons and holes. This diffusion currents are also called recombination currents, which are given by equation (2.43) and (2.44)

\[ I_p = I_{rec} = Aqp \frac{D_p}{L_p} \]  

(2.43)

\[ I_n = I_{rec} = Aqn \frac{D_n}{L_n} \]  

(2.44)

The immobile oppositely charged ions on the two sides of the junction establish a built in
electric field $E$ from n-region to p-region. This electric field drift the positively charged holes from n-region to p-region and electrons from p-region to n-region, this result in drift current (also called generation current) of the two carriers given by equation (2.45) and (2.46).

$$I_n = I_{gen} = Anq\mu_n E$$  \hspace{1cm} (2.45)

$$I_p = I_{gen} = Apq\mu_p E$$  \hspace{1cm} (2.46)

The direction of the drift of the two type of charge carrier is depicted in Figure (2.10) whereas the direction of diffusion in the opposite that direction.

![Diagram of charge carrier drift](image)

Figure (2.10) Direction of the drift current of charge carrier in p-n junction

At thermal equilibrium the drift current cancel the diffusion current, so the net current is equal zero or equivalently the recombination current cancel the generation current. A built in potential denoted by $V_{bi}$ or $V_0$ contact potential due to electric field produced, it is equal to the difference in the work function of p-side and n-side and is given by

$$V_0 = \frac{k_B T}{q} \ln \left( \frac{N_a N_d}{n_i^2} \right)$$  \hspace{1cm} (2.47)

where $N_a, N_d$ are acceptor and donor concentrations.
Once n-type and p-type brought in contact, the Fermi levels must align at the same level therefore, the bands have to bend to reach this condition. The bent from the p-type to the n-type regions. Moreover, the amount of band bending is directly related to the built-in potential as shown in Figure (2.11).

![Energy band profile across a p-n junction](image)

Figure (2.11) Energy band profile across a p-n junction (Razeghi, 2002)

2.10.2 p-n junction diode under non equilibrium conditions

When the p-n junction is exposed to external stimulus, such as applied bias or when it is illuminated, its properties deviate from its equilibrium state

2.10.3 Forward biased p-n junction diode

When a current source with voltage (V_a) is connected across a p-n junction so that the positive terminal is attached to the p-side and the negative terminal is attached to the n-side, the junction is said to be forward biased, as shown in Figure (2.12)
The presence of the external bias voltage causes a departure from equilibrium and misalignment of the Fermi levels in the n- and p- regions, as well as in the depletion region. The presence of two Fermi levels in the depletion region, $E_{f_c}$ and $E_{f_v}$ represent a state of quasi-equilibrium as shown in Figure (2.13).

Due to the high conductivity of the bulk region outside the depletion region, the potential barrier against diffusion reduced to be $(V_0 - V)$, where $V$ is the voltage applied $V = V_a$. Consequently many holes can diffuse across the depletion region and enter n-side.
Similarly electrons can diffuse towards the p-side. When holes are injected into the neutral n-side, they draw some electrons, from the bulk (and hence from the current source) so that there is a small increase in the electron concentrations. This small increase in the majority carriers is necessary to balance the hole charges and maintain neutrality in the n-side. The diffused hole in the n-region recombine with electrons, the electron lost by recombination is replenished by the negative terminal of the current source connected to this side. Similarly the injected electrons from n-region to the p-region, as they diffuse towards the positive terminal recombine with some of the many holes in this region. Those holes lost by recombination can be replenished by the positive terminal of the source to this side. The current due diffusion of electrons in the p-side can be maintained by the supply of electrons from the n-side which itself can be replenished by the negative of the source. In addition to diffusion currents of minority carriers, there also some drift currents of majority carriers. But the diffusion currents of minority carriers increase in the forward bias whereas the drift currents remain unchanged.

2.10.4 Reverse biased p-n junction diode

When the positive terminal of a current source is connected to n-side of p-n junction and the negative terminal is connected to p-region, the junction is said to be reverse biased, as depicted in Figure (2.14)
In case of reverse biased p-n junction the potential barrier is increased to \( V_0 + V \) and the electric field is increased also, so the depletion region become wider as depicted in Figure (2.15). The potential barrier impedes the flow of majority carriers and leaving only minority carriers. The reverse bias saturation is taken to be \((-I_0)\).

I-V characteristic take the general form

\[
I = I_0 \left( e^{\frac{qV}{kT}} - 1 \right)
\]  

(2.48)

The reverse saturation is given by

\[
I_0 = A q \left( \frac{p_{Dp}}{l_p} + \frac{n_{Dn}}{l_n} \right)
\]  

(2.49)

For high reverse applied voltage \( e^{\frac{qV}{kT}} \approx 0 \), the net current \( I = -I_0 \)

Since the current density \( J = A I \) equation (2.49) take the form

\[
J_0 = q \left( \frac{p_{Dp}}{l_p} + \frac{n_{Dn}}{l_n} \right)
\]  

(2.50)
Figure (2. 15) (d) Potential profile and (e) and energy band profile of a p-n junction under reverse bias $V < 0$.  (Razeghi, 2002)

The thick dashed curves represent the equilibrium case for comparison.

### 2.10.5 Application of p-n junction diodes

The applications of p-n junction diode is based on certain properties of p-n junction, these include:

I- The injection of electron–hole pair at the junction to generate light via recombination in devices like light emitting diodes (LEDs) and lasers.

II- The separation of electron- hole pair at the junction to constitute a current source in solar cells.

III- The temperature dependence of the I-V characteristic in temperature sensors

IV- The nonlinear nature of I- V characteristic in devices as frequency multiplier and mixers.

V- The device as a switch like rectifiers, inverter and power supply.

### 2.11 Solar cell: Structure and principle of operation

A solar cell is an electronic device which directly convert sunlight into electricity. Solar cells are described as being photovoltaic irrespective whether the source is sunlight or artificial light. Almost all solar cells contain junctions between different materials of different doping, since these junctions are crucial to the operation of the solar cell. A p-n junction fabricated in the same semiconductor material such as a silicon is an example of a p-n homojunction. There are also other types of junctions: A p-n junction that is formed by two chemically different semiconductors is called a p-n heterojunction. In a p-i-n junctions, the region of the internal electric field is extended by inserting an intrinsic (i)
layer between the p-type and the n-type layers. The i-layer behaves like a capacitor and it stretches the electric field formed by the p-n junction across itself. Another type of the junction is a junction between a metal and a semiconductor, a so-called multi junction. The Schottky barrier formed at the metal semiconductor interface is a typical example of the multi junction.

The operation of photovoltaic cell requires three basic attributes:
1-The absorption of light, generating electron-hole pair or excitons. 2- The separation of charge carriers of opposite types. 3- The separate extraction of those to an external circuit.

The solar cell structure and the equivalent circuit are depicted in Figure (2.16) and (2.18), respectively.

To know how p-n junction solar cell generates electric energy, it is important to bear in mind that at p-n contact the n-type region near the contact consists of positive ions, while the p-type region near the contact consists of negative ions. When light photons are incident and enter the depletion region, they are absorbed by the electrons in the valence band.
This causes transfer of electrons from the valence band to the conduction band. The final result is the accumulation of free electrons in the conduction band and holes in the valence band. Thus electron-hole pair are generated. The charge separation is performed by the ions located near the two sides of p-n contact. The free electrons are attracted by the positive ions at n-type, while the holes are attracted by the negative ions. The concentration of electrons become very high in the n-type near and in the depletion layer compared to the rest part of n-type. Thus an electric current is generated by diffusion due to the concentration gradient to cause electrons transfer and accumulation from depletion region to the remote edge part of the p-n junction which act now as a negative battery electrode The same hold for holes where holes diffuse from the depletion layer, where the concentration of holes is extremely large, to remote the edge from the p-n contact. As a result holes are highly accumulated at this edge forming a positive battery electrode as shown in Figure (2.17)
Figure (2.17) Charge separation in the solar cell

When no external contact between the n-type and p-type region, which means that the junction is open –circuit condition, no net current can flow inside. The electrostatic potential barrier across the junction is lowered by the open circuit voltage $V_{oc}$. Under illuminated p-n junction solar cell, the net current flowing in a load is determined as the sum of the photo- and thermal generation currents and recombination current and it is given by equation (2.51) and (2.52)

$$I = I_{rec} + I_{gen} - I_{ph}$$  
$$I = I_0 \left( e^{qV/kT} - 1 \right) - I_{ph}$$

Alternatively, the I-V curve of a solar cell is the superposition of the I-V curve in the dark with the lightgenerated current. (Lindholm et al., 1979)

Illumination shifts the I-V 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 is given by (2.52)

Figure (2.18): (a) A solar cell connected to an external load (b) Equivalent circuit, with a constant current source, a forward biased p-n junction and the external load. (Sze, 2007)

In Figure (2.18) $I_L = I_{ph}$, $(I_s = I_0)$ is reverse saturated current
However, in reality, no device is ideal and so the equation must be modified to account for potential losses that may arise:

\[
I = I_{ph} - I_0 \left( \exp \frac{e(V+IR_s)}{n k_B T} - 1 \right) - \frac{V+IR_s}{R_{sh}}
\]  

(2.53)

(Johan, 2005; Ellingson and Heben, 2014)

Here, \( n \) is the diode ideality factor, \( R_{sh} \) is shunt or parallel resistance, and \( R_s \) is series resistance. The series resistance arises from the cell's material resistance to the current flow, particularly through the front surface to the contacts (and it is a serious problem at high current densities under concentrated light). The parallel, or shunt, resistance is a problem of poorly rectifying devices (and it arises from leakage of current through the cell). Using this equation, a solar cell can be modeled using an equivalent circuit diagram that shown in Figure (2.19).

![Figure (2.19) The modeled equivalent circuit of solar cell](Johan, 2005; Ellingson and Heben, 2014)

The band diagram of illuminated solar cell is depicted in Figure (2.20)
The photo generated $I_{ph}$ or light current $I_l$ has three components, in the depletion region and in the n-type and p-type regions, and it is given by

$$I_{ph} = qAG (L_n + W + L_p)$$  \hspace{0.5cm} (2.54)

where $A$ is area of the solar cell, $G$ is the generation rate, $W$ is width of the depletion region. From equation (2.54) only carriers generated in the depletion region and in regions up to the minority carrier diffusion length from the depletion region contribute to the photo generated current. Both the dark and illuminated I-V characteristic of the p-n junction of the solar cell are shown in Figure (2.21).
Since the solar cell function as a forward-biased p-n junction and generate power to an external load, the illuminated curve is inverted in the first quadrant.

2.12 Solar Radiation.

The radiative energy output from the sun derives from a nuclear fusion reaction. In every second about $6 \times 10^{11}$ kg of H$_2$, is converted to He, with a net mass loss of about $4 \times 10^3$ kg, which is converted through the Einstein relation ($E = mc^2$) to $4 \times 10^{20}$ J. This energy is emitted primarily as electromagnetic radiation in the ultraviolet to infrared and radio spectral ranges (0.2 to 3 $\mu$m). The total mass of the sun is now about $2 \times 10^{30}$ kg, and a reasonably stable life with a nearly constant radiative energy output over $10^{10}$ years is projected. The intensity of solar radiation in free space at the average distance of the earth from the sun has a value of 1,353 W/m$^2$. The atmosphere attenuates the sunlight when it reaches the earth’s surface, mainly due to water-vapor absorption in the infrared, ozone (O$_3$) absorption in the ultraviolet, and scattering by airborne dust and aerosols. (Sze, 2007)
The degree to which the atmosphere affects the sunlight received at the earth's surface is quantified by the air mass. The path length of the solar radiation through the Earth’s atmosphere in units of Air Mass (AM) increases with the angle from the zenith. For a path length $L$ through the atmosphere and solar radiation incident at angle $\theta$ relative to the normal to the Earth's surface, the air mass coefficient (AM) is:

$$AM = \frac{L}{L_0} = \frac{1}{\cos \theta} = \sec \theta$$  \hspace{1cm} (2.55)

Where $L_0$ (the zenith path length) is perpendicular to the Earth's surface at sea level and $\theta$ is the zenith angle in degrees. The AM0 thus represents the solar spectrum outside the earth's atmosphere. The AM1 spectrum represents the sunlight at the earth's surface when the sun is at zenith, and the incident power is about 925 W/m². The AM2 spectrum is for $\theta = 60^\circ$ and has an incident power of about 691 W/m², and so on.

Figure (2.22) Solar Radiation Air Mass standards and corresponding Latitude

(BIN, 2015)

is the AM0 condition which can be approximated by a 5,800 K black-body radiation.
The AM0 spectrum is the relevant one for satellite and space-vehicle applications. The AM1.5 conditions (with sun at 48° above the horizon) represent a satisfactory energy-weighted average for terrestrial applications.

Solar energy can be captured in two forms, either as heat or as electrical energy.
1-Thermal Systems: Thermal systems capture the Sun's heat energy (infra-red radiation) in some form of solar collector and use it to mostly to provide hot water or for space heating, but the heat can also be used to generate electricity by heating the working fluid in heat engine which in turn drives a generator.
2- Photovoltaic Systems: Photovoltaic systems capture the sun's higher frequency radiation (visible and ultra violet) in an array of semiconductor, photovoltaic cells which convert the radiant energy directly into electricity.

2.13 Detailed Balance Limit of Efficiency of p-n Junction Solar Cells
The Shockley–Queisser limit refers to the maximum theoretical efficiency of a solar cell using a single p-n junction to collect power from the cell. It was first calculated by William Shockley and Hans-Joachim Queisser at Shockley Semiconductor in 1961. Shockley and Queisser developed a formalism to calculate the limit of efficiency of a p-n-junction solar cell (Shockley and Queisser, 1961) they suggested that the generation of carriers in the semiconductor is defined by a detailed balance between light absorption and radiative recombination. Ideally, the carrier mobility is infinite, and the position of the Fermi level is quasi-invariant. Also ideally, the surface recombination velocity is zero. In equilibrium, the energies of two quasi-Fermi levels (\(E_{\text{FV}}\) for the p-type semiconductor and \(E_{\text{FC}}\) for the n-type semiconductor) are the same. The electric contact between semiconductors of two types is supposed to be ideal. The voltage \(V\) appearing between the two electrodes is defined by the difference in the quasi- Fermi levels of the majority carriers and can be obtained from the following equation:

\[
e V = E_{\text{FC}} - E_{\text{FV}} \tag{2.56}
\]

The total power density of the Sun radiation \(H\) can be found from the Stefan-Boltzmann law:

\[
H = \sigma T_s^4 \tag{2.57}
\]

Where \(\sigma\) is the Stefan-Boltzmann constant, \(T_s = 5800\) K is the temperature of the sun.

When light absorption occurs in the semiconductor, the electrons make a transition from the valence band to the conduction band (the generation of electron-hole pair takes place). In accordance with the principle of a detailed balance, the reverse process also takes place so the electrons make back transition from the conduction band to the valence band and emit photons. This process is called a radiative recombination. Ideally, the absence of any nonradiative recombination mechanism is supposed. The difference between the number of absorbed and emitted photons determines the limit of the photocurrent. Density \(J_{\text{ph}}\) in semiconductors

\[
J_{\text{ph}} = e(\Phi_s - \Phi_r) \tag{2.58}
\]

Where \(\Phi_s\) and \(\Phi_r\) are the photon fluxes incoming and outgoing the solar cell, respectively. The streams of photons are determined by Planck’s equation

\[
\Phi_s = \frac{2 \pi \sin^2 \theta_s}{h^3 c^2} \int_{E_g}^{\infty} \frac{e^2}{E \exp \frac{E}{kT_s} - 1} dE \tag{2.59}
\]

\[
\Phi_r = \frac{2 \pi}{h^3 c^2} \int_{E_g}^{\infty} \frac{e^2}{E \exp \frac{E}{kT_d} - 1} dE \tag{2.60}
\]
where $\xi$ is the absorptivity or the emissivity (according to Kirchhoff’s law of thermal radiation we consider that the absorptivity is equal to the emissivity); $\theta_s$ is the solid angle at which the sun can be seen; $T_a$ is the temperature of the semiconductor; $h$ is Planck's constant; $c$ is the speed of light; $k$ is Boltzmann's constant; $E_g$ is the band-gap width. Shockley and Queisser supposed that all incident photons with the energies above the band-gap energy are absorbed, $\xi = 1$

The maximum limit for the photo generated electric current density $J_{ph}$ is therefore given by the flux of photons with an energy $h\nu > E_g$. Thus, $J_{ph}$ decreases with increasing band gap $E_g$. At the same time, the net energy transferred to each electron-hole pair increases, as it is equal to $E_g$. There exists an optimum for $E_g(1.1 \text{ eV})$ for which a maximum of energy can be transferred from the incident sunlight to the totality of photo generated electron-hole pairs. At this band gap, roughly half of the incident solar energy is transferred. This limit will only be approached if optical Losses due to reflections, shading by grid patterns, and so forth are minimized and if the semiconductor is thick enough to absorb all useful incident photons. The latter condition is particularly difficult to fulfill in semiconductors with an indirect band gap (such as crystalline silicon).

The photo generated current density $J_s$ of a solar cell can be obtained by integrating the total area under the graph of flux of photon $\Phi$ vs photon energy $h\nu$ in the plot of $\Phi$ vs $h\nu$

$$J_s(E_g) = q \int_{h\nu=E_g}^{\infty} \frac{d\Phi_{ph}}{dh\nu} d(h\nu)$$ (2.61)

2.14 Quantum confinement effect

The quantum behavior of particles is best observed in small, typically nanometer scale. In such small structures in a crystal, the motion of an electron can be confined in one or more directions in space. As a result of these “geometrical” constraints, electrons “feel” the presence of the particle boundaries and respond to changes in particle size by adjusting their energy. This phenomenon is known as the quantum-size effect. Quantization effects become most important when the particle dimension of a semiconductor near to and below the bulk semiconductor Bohr exciton radius which makes materials properties size dependent. When the particle size approaches Bohr exciton radius, the quantum confinement effect causes increasing of the excitonic
transition energy and blue shift in the absorption and luminescence band gap energy. In addition, quantum confinement leads to a collapse of the continuous energy bands of a bulk material into discrete, atomic like energy levels. The discrete structure of energy states leads to a discrete absorption spectrum, which is in contrast to the continuous absorption spectrum of a bulk semiconductor. A quantum confined structure is one in which the motion of the carriers (electron and hole) are confined in one or more directions by potential barriers. Based on the confinement direction, a quantum confined structure will be classified into three categories as quantum well, quantum wire and quantum dots or nanocrystals. The basic type of quantum confined structure is shown in Table 2.1.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Quantum confinement</th>
<th>Number of free dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Quantum well/super lattices</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Quantum wire</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Quantum dot/Nanocrystals</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

In QDs, the charge carriers are confined in all three dimensions which the electrons exhibit a discrete atomic-like energy spectrum. Quantum dots are commonly known as “artificial atoms” because they provide the opportunity to control the energy of carrier states by adjusting the confinements in all three spatial dimensions. With QDs closely packed, the confined levels overlap to form minibands in QD superlattices. Quantum wires are formed when two dimensions of the system are confined. In quantum well, charge carriers (electrons and holes) are confined to move in a plane and are free to move in a two-dimensional. Also the energy level of one of the quantum numbers changes from continuous to discrete. Compared with bulk semiconductors, the quantum well has a higher density of electronic states near the edges of the conduction and valence bands,
and therefore a higher concentration of carriers can contribute to the band-edge emission. Density of electron states in bulk, 2D, 1D and 0D semiconductor structure is shown in Fig. 2.1 0D structures has very well defined and quantized energy levels. Optical properties are connected with electronic structure, a change in zone structure leads to a change in absorption and luminescence spectra. Nanoparticles are intermediate in size between atoms and solid.

Figure (2.24) The energy distribution of possible electronic energy levels is drastically affected by spatial confinement (Lewis et al., 2005)

The optical absorption spectrum is roughly proportional to the density of states. This method can predict the confined energy levels of nanostructures by solving Schrodinger equation assuming the barriers have an infinite confining potential.

Zero-dimensional structures: quantum dots:

An ideal quantum dot, also known as a quantum box, is a structure capable of confining electrons in all three dimensions, thus allowing zero dimension (0D) in their degrees of freedom. In quantum dots, there is thus no possibility for free particle-like motion. The energy spectrum is completely discrete, similar to that in an atom. A quantum dot
can be imagined as quantum box. Assuming $\Psi_n(r)$ is the wave function of the nth state. Schrödinger equation for an electron confined in one-dimensional infinite square potential well of size $L$ is:

$$\frac{-\hbar^2}{2m} \frac{d^2}{dx^2} \psi_n(x) + V(x) \psi_n = E_n \psi_n$$  \hspace{1cm} (2.62)

The energy eigenvalues $E_n$ and eigen-wavefunction $\psi_n(r)$ of the Schrödinger equation are given

$$\psi_n(x) = \sqrt{\frac{2}{L}} \sin \left( \frac{n\pi}{L} x \right) + \sqrt{\frac{2}{L}} \cos \left( \frac{n\pi}{L} x \right)$$  \hspace{1cm} (2.63)

$$E_n = \frac{\pi^2 \hbar^2}{2mL^2} n^2 \hspace{1cm} , n = 1, 2, 3, ... \hspace{1cm} (2.64)$$

If we extend the confinements of electron in three-dimensional potential well (box with dimensions $L_x$, $L_y$, and $L_z$) its momentum and energy will be quantized in all dimensions and we have:

$$E_n(x, y, z) = \frac{\pi^2 \hbar^2}{2mL^2} \left( \frac{n_x^2}{L_x^2} + \frac{n_y^2}{L_y^2} + \frac{n_z^2}{L_z^2} \right)$$  \hspace{1cm} (2.65)

With quantum dot (cubic box) of side dimension $L_x = L_y = L_z = L$, then $E_n$ is written as:

$$E_n(x, y, z) = \frac{\pi^2 \hbar^2}{2mL^2} \left( n_x^2 + n_y^2 + n_z^2 \right)$$

$$E_n(x, y, z) = \frac{\pi^2 \hbar^2}{2mL^2} n^2$$  \hspace{1cm} (2.66)

Similar energy eigenvalues can be written for holes. Considering spherical shape of quantum dot with radius $R$, based on the effective mass model developed by Louis Brus for colloidal quantum dots. The band gap $E_{QD}^*$ can be approximated by:

$$E_{QD}^* = E_{g}^{bulk} + \frac{\pi^2 \hbar^2}{2R^2} \left( \frac{1}{m_e} + \frac{1}{m_h} \right) - \frac{1.8e^2}{4\pi\varepsilon_0 R}$$  \hspace{1cm} (2.67)

where $\varepsilon$ is the relative permittivity, and $\varepsilon_0 = 8.854 \times 10^{-14}$ F cm$^{-1}$ the permittivity of free space. In Equation (2.67), the first term on the right hand side describes the energy bandgap value of the bulk, the second term represents particle in a box quantum confinement model, and the third term details the Coulomb attraction between electron and hole (exciton). As the radius of the quantum dot decreases the Coulomb attraction term could be neglected compared to the second term in calculations. Therefore, Equation (2.67) indicates that bandgap energy eigenvalues increases as the quantum dot size decreases. Since a quantum dot bandgap is tunable depending on its size, the smaller the
quantum dot the higher energy is required to confine excitons into its volume. Also, energy levels increase in magnitude and spread out more. Therefore, exciton characteristic peak is blue shifted. Quantum dot structured materials can be used to create the so called intermediate band. The large intrinsic dipole moments possessed by quantum dots, lead to rapid charge separation. Solar cells based on intermediate bandgap materials are expected to achieve maximum theoretical efficiency as high as 65%. (Ebrahim, 2015)

Unlike bulk semiconductors such as crystalline silicon, quantum dots can generate multiple exciton (electron-hole pairs) after collision with one photon of energy exceeding the bandgap. In bulk semiconductor absorption of photon with energy exceeding the bandgap promotes an electron from the valance band to higher level in the conduction band these electrons are called hot carrier. The excited electron (hot carrier) undergoes many nonradiative relaxation (thermalization: multi-phonon emission) before reaching the bottom of the conduction band. However, in a quantum dot the hot carrier undergoes impact ionization process (carrier multiplication). Therefore, absorption of a single photon generates multiple electron-hole pairs. This phenomena is called multiple exciton generation MEG. Therefore, absorption of UV photons in quantum dots produces more electrons than near infrared photons. (Nozik, 2002; Nozik, 2008).
The power generated by a solar cell is determined by the product of the photocurrent and the voltage across the diode. In conventional solar cells, both of these parameters are determined by the band gap of the semiconductors used. Large photocurrents are favoured by narrow gap materials, because semiconductors only absorb photons with energies greater than the band gap, and narrow gap materials therefore absorb a larger fraction of the solar spectrum. However, the largest open circuit voltage that can be generated in a p-n device is the built-in voltage which increases with the band gap of the semiconductor. Quantum well devices can give better performance than their bulk counterparts because they permit separate optimisation of the current and voltage generating factors. (Razeghi, 2002).

### 2.15 Solar cell performance

The performance of a solar cell is determined by the parameters, viz., short circuit current density ($J_0$), open circuit voltage ($V_{oc}$), fill factor (FF), and efficiency ($\eta$). The temperature variation affects these parameters. (Green, 1982)

The diode parameters of solar cells, i.e., reverse saturation current density ($J_0$) and ideality factor ($n$) along with series resistance ($R_s$) and shunt resistance ($R_{sh}$) control the effect of temperature on $V_{oc}$, FF and $\eta$ of the cell. The fill factor (FF) is the ratio of the actual power of the cell to what its power would be if there were no series resistance and infinite shunt resistance. This is ideally as close as possible to 1. The FF factor is a parameter which defines the degree of non-ideality of an actual cell, and it’s a measure of the sharpness of the I-V curve.

$$FF = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}} = \frac{V_{max}I_{max}}{V_{oc}I_{sc}} \quad (2.68)$$

The power conversion efficiency ($\eta$) of the solar cell is the ratio of output electrical power to the incident light power

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{mp}I_{mp}}{P_{in}} = \frac{V_{oc}I_{scFF}}{P_{in}} \quad (2.69)$$

The conversion efficiency is one of the most important parameters when discussing photovoltaic or any other energy conversion devices, telling us the ratio between output
and input energy. The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency depends on solar spectrum, intensity of sunlight and the temperature of solar cell (Kalogirou, 2009; Bhalchandra et al., 2015). Besides the actual state of the art average or record efficiencies, theoretical limiting efficiency is also very important since it declares how much progress is still left to achieve. In photovoltaic, the first limiting efficiency for solar cells was calculated by Shockley and Queisser in 1961.

In their work they assumed the detailed balance principle based on the second law of thermodynamics. Different techniques were examined in an attempt to achieve or even exceed the limiting efficiency. Most popular are light management through optical light scattering, tandem solar cells and concentrator solar cells. Other approaches, such as multiple exciton generation and up- and down-conversion, are also researched.

The power $P$ generated by the solar cell is given by

$$ P = IV = I_0V \left( e^{\frac{qV}{kT}} - 1 \right) - I_{ph}V $$

(2.70)

The condition for maximum power can be obtained when $\frac{dP}{dV} = 0$

$$ I_{max} = I_0 \beta V_{max} \exp(\beta V_{max}) \approx I_{ph} \left( 1 - \frac{1}{\beta V_{max}} \right) $$

(2.71)

$$ V_{max} = \frac{1}{\beta} \ln \left[ \frac{I_{ph}V_{oc} + 1}{1 + \beta V_{max}} \right] $$

(2.72)

The maximum power output $P_{max}$ is then

$$ P_{max} = FFI_0 V_{oc} \approx \left[ V_{oc} - \frac{1}{\beta} \ln(1 + \beta V_{max}) - \frac{1}{\beta} \right] $$

(2.73)

$$ V_{max} + \frac{K}{q} \ln \left( 1 + \left( \frac{qV_{max}}{K} \right) \right) = V_{oc} $$

(2.74)

The maximum current $I_{max}$ can be obtained letting $\frac{dP}{dI} = 0$

$$ I_{max} = -\frac{V_{max}I_0q}{nKT} e^{\frac{qV_{max}}{nKT}} $$

(2.75)

where $n$ is the ideality factor for ideal solar cell $n = 1$

The $I_0$ depends on the area of the solar cell. In order to remove the dependence of the solar cell area on $I_0$, often the short-circuit current density is used to describe the maximum current delivered by a solar cell. The maximum current that the solar cell can
deliver strongly depends on the optical properties of the solar cell, such as absorption in the absorber layer and reflection.

To reduce optical losses of the solar cell:

(i) The contact coverage should be minimized to maximize the surface that is exposed to light, (although this may result in increased series resistance). The area that is covered by the electrode effectively decreases the active area of the solar cell through which the light enters the solar cell. When we denote the total area of the cell \( A_{\text{tot}} \) and the cell area that is not covered by the electrode \( A_f \), the active area of the cell is determined by the ratio of \( A_f / A_{\text{tot}} \). This ratio is called the coverage factor which determines shading losses. Due to the limited thickness of the absorber layer, not all the light entering the absorber layer is absorbed.

(ii) The reflection is reduced by applying anti-reflection coatings this can be achieved if the refractive index of the anti-reflection coating is the geometric mean of that of the material. The factors affecting the solar cell performance include:

1- Characteristic resistance: The characteristic resistance of a solar cell is the output resistance of the solar cell at its maximum power point. If the resistance of the load is equal to the characteristic resistance of the solar cell, then the maximum power is transferred to the load and the solar cell operates at its maximum power point.

2- Parasitic Resistances: Resistive effects in solar cells reduce the efficiency of the solar cell by dissipating power in the resistances. The most common parasitic resistances are series resistance and shunt resistance. In most cases and for typical values of shunt and series resistance, the key impact of parasitic resistance is to reduce the fill factor. Both the magnitude and impact of series and shunt resistance depend on the geometry of the solar cell, at the operating point of the solar cell. Impact of both resistances on the solar cell could seriously reduce the fill factor. For an ideal solar cell, series resistance equals to 0 ohms while shunt resistances equals to infinity.

3- Temperature: Solar cells are sensitive to temperature. Increases in temperature reduce the band gap of a semiconductor, thereby effecting most of the semiconductor material parameters. In a solar cell, the parameter most affected by an increase in temperature is
the open-circuit voltage. As the temperature increases, the open-circuit voltage decreases, thereby decreasing the fill factor and finally decreasing the efficiency of a solar cell.

4- Light intensity: Changing the light intensity incident on a solar cell changes all solar cell parameters, including the short-circuit current, the open-circuit voltage, the fill factor, the efficiency and the impact of series and shunt resistances. At low light levels, the effect of the shunt resistance becomes increasingly important. Consequently, under cloudy conditions, a solar cell with a high shunt resistance retains a greater fraction of its original power than a solar cell with a low shunt resistance.

5 -Ideality factors: The ideality factor of a diode is a measure of how close the diode follows the ideal diode equation.

Figure (2.26): The loss mechanisms in single junction solar cells:
(1) missed absorption of low energy photons (2) thermalization of hot carriers (3) junction loss (4) non-ideal contacts (5) recombination. (Conibeer, 2007)

2.16 The solar cells evolution takes 4 generation steps

With the use of various materials and techniques, the fabrication of solar cells has been passed through large number of improvements from first generation to another on the basis of low cost and high efficiency. Solar cells based on silicon were the first generation solar cells grown on silicon wafer with disadvantage of high cost and low efficiency. With further development towards thin films, second generation of solar cell fabrication technologies to produce electrical energy came into existence with enhanced cell efficiency. Thin film solar cells consist of different layers which help to reduce the current losses. That’s why as compared to the traditional silicon solar cells, thin film solar cells have high efficiencies. Researchers have followed the development in solar cells from one generation to another and compared between the different types of generations.

2.16.1 1st Generation Solar Cells (Crystalline silicon (c-Si) PV technology):

Photovoltaic effect was first recognized by the French physicist, Aleixandre-Edmond Becquerel in 1839, but the first modern solar cell with enough efficiency for power applications was not developed until 1954 at Bell Labs in New Jersey in 1954. While experimenting with semiconductors, Bell lab accidentally found that silicon doped with certain impurities was very sensitive to light. This is the birth of 1st generation solar cell technology. It is Silicon-based technology and is the dominant technology in the commercial production of solar cells, accounting for more than 86% of the solar cell market. It is technically proven and reliable, and has succeeded in achieving market penetration, primarily in off-grid remote areas and lately in grid-connected applications. There are however, several inherent limitations to this 1st generation technology from the onset. Silicon wafers are very fragile and the process involved in the manufacturing is difficult and labor intensive, hence high cost. There are two approaches to manufacturing crystalline silicon based solar cells; single crystal and multi-crystalline cells. The Single crystal silicon wafers (c-Si) or the Mono-crystalline Solar Cells in which the crystal lattice of the entire sample is continuous and unbroken with no grain boundaries is still
one of the most efficient photovoltaic solar cells to date. The process of production involves crystalline silicon rods being extracted from melted silicon and then sawed into thin plates. About half of the manufacturing cost comes from wafering; a time-consuming and costly batch process in which ingots are cut into thin wafers with a thickness of about 200 micrometers. If the wafers are too thin, the entire wafer will break in the process and due to this thickness requirement, a PV cell requires a significant amount of raw silicon and close to half of this not very inexpensive material is lost as sawdust in the wafer processes. The polycrystalline approach uses discrete cells on silicon wafers cut from multicrystalline ribbons; the process is less expensive than the single crystalline cells. Though it is more expensive, Mono-crystalline silicon cells are generally more durable and efficient and produce more wattage per square foot than their polycrystalline cell counterpart. Other advantages of crystalline silicon based solar cells are that they have broad spectral absorption range and high carrier mobility. The efficiency of mono-crystalline silicon solar cell currently peaks at about 28% while poly-crystalline cells are approaching about 20% (Wohlgemuth and Narayanan, 1991)

2.16.2 2nd Generation Solar Cells:
(Thin-film Technology Solar Cells)
Because of the high cost of manufacturing of the 1st generation solar cells, a 2nd Generation solar cells known as thin film technologies was developed. The technology involves depositing a thin layer of photo-active material (Non-crystalline silicon) onto inexpensive substrates material using plasma enhanced chemical vapor deposition (PECVD) process. Amorphous semiconductor material (a-Si) is commonly used. An amorphous material differs from crystalline material in that there is no long-range order in the structural arrangement of the atoms. Although the thin film PV cells are less subject to breakage and not vulnerable to most of the other manufacturing problems that are common to the crystalline solar cells, its efficiency is significantly lower. The efficiency of thin film technologies solar cell is approaching about 20% based on recent research breakthroughs (Wohlgemuth and Narayanan, 1991)

2.16.3 3rd Generation Solar Cells:
The 3rd generation solar cells involve different Semiconductor Technologies that are
fundamentally different from the previous semiconductor devices. It has been estimated that 3rd generation solar technologies will achieve higher efficiencies and lower costs than 1st or 2nd generation technologies (Zweibel et al., 2008). Some of these technologies are Nanocrystal Solar Cells, Photo-electrochemical cells, Dye-sensitized hybrid solar cells and Polymer Solar cells. Nanocrystal solar cell technology is based on grains of nanocrystals or quantum dots. Examples are Lead selenide (PbSe) semiconductor and Cadmium telluride (CdTe) semiconductor. Quantum dots have band-gaps that are tunable across a wide range of energy levels by changing the quantum dot size. This is in contrast to crystalline materials, where the band-gap is fixed based on the material composition. This property makes quantum dots viable for multi-junction solar cells, where a variety of different band-gap materials are used to optimize efficiency by harvesting select portions of the solar spectrum. Additional advantages of these cells are; Low-energy and high-throughput processing technologies, low material cost, performs even at low incident light conditions. The disadvantage is that efficiency is still lower than silicon wafer based solar cells and also there is a risk of material degradation overtime. The efficiency of this type of solar cell is approaching about 11% (Wohlgemuth and Narayanan, 1991)

2.16.4 4th Generation Solar Cells:
This category of solar cells combined the 3rd generation technologies to form the 4th generation solar cells technology. Example is the nanocrystal /polymer solar cell, a Composite photovoltaic cell technology which combines the elements of the solid state and organic PV cells to form the Hybrid-nanocrystalline oxide polymer composite cell. Although most of these technologies are still in the embryonic development stage, it is predicted that because of the lower cost of material, this type of solar cell would significantly make solar deployment affordable. Another area where Photovoltaic solar cell technology has achieved significant efficiency milestone is in the concentrator solar cell technology. Example is the multi-junctions (III-Vs) solar cells which has recorded efficiency of greater than 41% (Zweibel et al., 2008) The National Renewable Energy Laboratory (NREL) maintains a plot of compiled values of highest confirmed conversion efficiencies for research cells, from 1976 to the present,
for a range of photovoltaic technologies. This chart highlights cell efficiency results within different families of semiconductors: (1) multijunction cells, (2) single-junction gallium arsenide cells, (3) crystalline silicon cells, (4) thin film technologies, and (5) emerging photovoltaics.

Figure (2.27) Evolution of the conversion efficiencies of various types of research PV cells (NREL, 2016)

2.17 Types of photovoltaic solar cell

Photovoltaic cells can be divided into three categories:
1- Inorganic cells, based on solid-state inorganic semiconductors;
2- Organic cells, based on organic semiconductors; and
3- Photoelectrochemical cells, based on interfaces between semiconductors and molecules.

One difference between inorganic and organic photovoltaic cells is that in organic cells, the electrons and holes are initially bound to each other in pairs called excitons; these excitons must be broken apart in order to separate the electrons and holes to generate electricity. In inorganic photovoltaic cells, the electrons and holes created by the absorption of light are not bound together and are free to move independently in the semiconductor. (Reddy, 2012)

2.17.1 Silicon solar cells

The first Si p-n cells were developed at Bell Labs (USA) in 1954. (Chapin et al., 1954). They had an efficiency of about 6%, but their potential as power supply for space satellites soon became clear. The first extensive and important solar cells application occurred in 1958, on both the Soviet satellite Sputnik 3 and the US Vanguard, which mounted 8% efficiency n-type Si with diffused boron as p dopant. The success of Si in space also came from the technical know-how derived from electronic applications, such as power converters (AC to DC current conversion, HF generation), and electronic circuits for radio communications, to the availability of several growth techniques and ohmic contact deposition. Since these pioneering applications, Si solar cells have become more and more used in space, and a lot of efforts have been made to increase their efficiency and reliability, in order to obtain better radiation resistant material. Advances in crystal growth technology have permitted to obtain materials with a higher degree of purity and high carrier lifetimes (>1 µs). In the 1970s cheaper Si modules with lower efficiencies were tested, either amorphous, polycrystal, (Spear and LeComber, 1972; Dietl et al., 1981) or thin film based.24,25 Until 1970 Si was the only available power source for space missions, reaching a conversion efficiency of 14–15%. The stringent requirements that solar cells had to meet made cost optimization a minor problem: the high price of solar cells in the ‘70s and 80’s was the main reason for their limited use on Earth, often confined to small electronic devices such as calculators or watches.
2.17.2 Thin Film Solar Cell

Silicon as a solar cell material has many advantages. However, it also has a disadvantage, silicon is an indirect semiconductor. The absorption coefficient near its band edge is low. Therefore, a fairly thick substrate is required. The wafer is cut from a single crystal or an polycrystal ingot. The minimum thickness to maintain reasonable absorption and mechanical strength is 0.1 – 0.2 mm. The cost of the material and mechanical processing is substantial. The direct semiconductors often have an absorption coefficient one or two orders of magnitude higher than silicon for those materials, a thickness of a few micrometers is sufficient.

A thin-film solar cell is a second generation solar cell that is made by depositing one or more thin layers, or thin film of photovoltaic material on a substrate, such as glass, plastic or metal. Thin-film solar cells are commercially used in several technologies, including cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and amorphous and other thin-film silicon. Film thickness varies from a few nanometers (nm) to tens of micrometers (μm), much thinner than thin-film's rival technology, the conventional, first-generation crystalline silicon solar (c-Si) that uses silicon wafers of up to 200 μm. This allows thin film cells to be flexible, lower in weight, and have less drag. It is used in building integrated photovoltaic and as semi-transparent, photovoltaic glazing material that can be laminated onto windows. Other commercial applications use rigid thin film solar panels (sandwiched between two panes of glass) in some of the world's largest photovoltaic power stations. Copper oxide semiconductors are a promising alternative to silicon-based solar cells because Cu$_2$O possess high optical absorption and composed of low cost materials. ZnO has been used for a good electron acceptor and n-type semiconductor for Cu$_2$O/ ZnO hetero-junction solar. Mittiga E, and others studied the performance of copper oxide-zinc oxide Cu$_2$O/ZnO and CuO/ZnO thin film solar cells fabricated by electro deposition. They reported that a solar cell with a FTO/ZnO/ Cu$_2$O structure provided power conversion efficiency (η) of 0.25 %, fill factor (FF) of 0.33, and short-circuit current density (J$_{SC}$) of 2.7 mA cm$^{-2}$ and open-circuit voltage (V$_{OC}$) of 0.28 V under an air mass 1.5 illumination (Mitiga et al., 2006; Kazuya et al.,2013)

Cadmium telluride CdS/CdTe is an excellent direct band material with an optimum band gap (1.45 eV), and a large absorption coefficient requiring only a few microns thick
material to absorb nearly 100% of the solar spectrum with energies \( > 1.45 \text{ eV} \). Theoretically, CdTe solar cells are estimated to achieve efficiencies up to 27\% (Loferski, 1956; Adirovich, 1969) fabricated the first p- CdTe/n- CdS heterojunction solar cell with efficiency of 1\% . Cadmium telluride thin films conversion efficiencies of up to 16.5\% have been reported at the National Renewable Energy Laboratory – NREL. Modules with 60 Wp, 0.72 m\(^2\) and 8\% efficiency were commercialized, in modest scale, in Europe and in the USA. CdTe modules were manufactured by First Solar, based in Ohio, were selected for a 1.3 MW German solar power plant. SM Shamim, and others studied the effect of doping on windows layer (ZnO), buffer layer (CdS) and absorption layer (CIGS) in the CIGS solar cell. The device parameters are optimized separately for each layer. Energy conversion efficiency is calculated from light J-V characteristic. A total- area efficiency of 19.75\% ZnO: Al/i-ZnO/CdS/CIGS based film solar cell has been reported.

### 2.17.3 Organic Solar Cells

Organic solar cells consist of hydrocarbon compounds, deposited as ultrathin layers (some tens of nm) on a substrate. Absorption of light leads to molecular excited states (excitons) which are strongly bound due to the weak interactions and low dielectric constant in a molecular solid. The excitons have to be split into positive and negative charges, which are subsequently collected at different electrodes. Organic materials used in solar cells include conducting polymers, dyes, pigments and liquid crystals. Among these conductive polymers, are perhaps the best known for their photo-physical properties. Conjugated polymers and molecules have the immense advantages of simplicity and chemical tailoring to alter their properties, such as the band gap. Conjugated polymers combine the electronic properties characteristic of traditional semiconductors and conductors with the simplicity of processing and mechanical flexibility of plastics. There is no shortage in raw materials needed to make organic semiconductors. Molecules with a large molecular weight (\( > 1000 \text{ amu} \)) are referred to as 'polymers' and lighter ones as 'small molecules'. Compared to existing technologies there are several factors that attract global commercial interest in these organic semiconductors such as:
(i) Ability to be deposited at room temperature on a variety of low cost substrate materials (plastic, glass, metal foils) (ii) relative ease of processing.
(iii) Materials inherently flexible and readily available.
(iv) ultra-low cost, and (v) environment-friendly
In contrast to inorganic semiconductors, organic semiconductors have lower dielectric constant and larger exciton binding energy, therefore, the thermal energy at room temperature is not sufficient to dissociate the exciton and generate free carriers.
(Reddy, 2012)

2.17.4 Multi junction Solar Cells
Multi-junction (MJ) solar cells are solar cells with multiple p–n junctions made of different semiconductor materials. Each material's p-n junction will produce electric current in response to different wavelengths of light. The use of multiple semiconducting materials allows the absorbance of a broader range of wavelengths, improving the cell's sunlight to electrical energy conversion efficiency. Traditional single junction cells have a maximum theoretical efficiency of 34%. Theoretically, an infinite number of junctions would have a limiting efficiency of 86.8% under highly concentrated sunlight. (Spear and LeComber, 1972) Commercial examples of tandem, two layer, cells are widely available at 30% under one-sun illumination and improve to around 40% under concentrated sunlight. However, this efficiency is gained at the cost of increased complexity and manufacturing price. Their higher price and higher price-to-performance ratio have limited their use to special roles, notably in aerospace where their high power-to-weight ratio is desirable. In terrestrial applications these solar cells have been suggested for use in concentrated photovoltaics (CPV), with numerous small test sites around the world. Tandem fabrication techniques have been used to improve the performance of existing designs. In particular, the technique can be applied to lower cost thin-film solar cells using amorphous silicon, as opposed to conventional crystalline silicon, to produce a cell with about 10% efficiency that is lightweight and flexible. This approach has been used by several commercial vendors, but these products are currently limited to certain niche roles, like roofing materials. Multi-junction solar cells use multiple semiconductor layers to produce electricity at high operating efficiencies. Each layer has a unique band gap designed to efficiently absorb a specific segment of the solar spectrum. This has two
important advantages over single-junction (SJ) devices: a wider range of absorption of incident photons as well as a more effective energy extraction from these photons. The lowest band gap of a MJ cell will be lower than that of a typical SJ band gap. Therefore, the MJ cell can absorb extra photons that possess less energy than the SJ band gap but greater than its own lowest band gap. The MJ cell will absorb the same photons more efficiently since having band gaps closer to the photon energy will reduce thermalization losses.

![Multi junction Solar Cell](image1.png)

**Figure (2.28)** (a) Multi junction Solar Cell  (b) Wavelength vs Irradiance  
(Kitai, 2011)

### 2.17.5 Polymer Solar Cell

The basic principle behind both the polymer solar cell and other forms of solar cells, is the same, namely the transformation of the energy in the form of electromagnetic radiation (light) into electrical energy (a current and a voltage). The fact that polymers can behave as semiconductors is a discovery which Alan J. Heeger, Alan MacDiarmid and Hideki Shirakawa received the Nobel Prize in Chemistry for in the year 2000. This
discovery of conjugated polymers being able to transfer electrons upon doping with iodine made it possible to prepare solar cells from polymers and thereby a new research area was born. Polymer solar cells have for a long time lagged behind traditional solar cells on both performance and stability. However, they have always had a potential advantage; that is their ability to be produced from solution. This means that they can be printed or coated, instead of using expensive vacuum deposition as for the first generation silicon solar cells. Performances of 10% have been demonstrated for polymer solar cells (Licht, 2001). The lifetime has also improved considerably and plastic solar cells with a shelf life of several years have been demonstrated. A polymer solar cell is a type of flexible solar cell made with polymers, large molecules with repeating structural units. Polymer solar cells include organic solar cells (also called "plastic solar cells"). They are one type of thin film solar cell, others include the more stable amorphous silicon solar cell. Compared to silicon-based devices, polymer solar cells are lightweight (which is important for small autonomous sensors), potentially disposable and inexpensive to fabricate (sometimes using printed electronics), flexible, customizable on the molecular level and potentially have less adverse environmental impact. Polymer solar cells also have the potential to exhibit transparency, suggesting applications in windows, walls, flexible electronics, etc. Listing the advantages of polymer solar cells reveals a very enticing selling point; however, polymer solar cells have a number of drawbacks. Firstly, while inorganic silicon-based solar cells may last on the order of 25 years; polymer based devices struggle to last a year. Efficiency has long remained the other major drawback of the technology. With polymer solar cell the efficiency is still behind more traditional technologies, but records exceeding 10% have been reported. (Krebs et. al. 2007)

For polymer solar cells to mature to the market, the strong points of the technology will have to match the weak points. However, it is still vital to optimize the weak points. Professor Fredrik C. Krebs have defined the unification challenge of polymer solar cells by stating that three issues share the same importance.(Green et al.,2012) These three issues were defined as; process, stability, and efficiency. The concept is very similar to the critical triangle for photovoltaics as presented by Professor Christoph J. Brabec, however substituting processability for cost. While no issue can be argued more important than another, the efficiency of solar cells have long been given special
attention. As an area of focus, the power conversion efficiency is important in order to compete with the more mature silicon technology and to justify research in the field of polymer solar cells. As long as focus of research is not on all of the areas, progress towards application of the technology will remain slow. Within recent years the number of reports on both processability and stability has increased significantly. Roll-to-roll production is becoming an established technique for producing polymer solar cells.

![Organic Solar Cell (with polymers)](image)

Figure (2.29) Organic solar cell with polymer. (Lewis, 2005)

### 2.17.6 Perovskite Solar Cell
The perovskite material is derived from the calcium titanate (CaTiO$_3$) compound, which has the molecular structure of the type ABX$_3$. Perovskite materials have attracted wide attention because of the cubic lattice-nested octahedral layered structures and the unique
optical, thermal, and electromagnetic properties. Perovskite materials used in solar cells are a kind of organic-inorganic metal halide compound with the perovskite structure, in which Group A (methyl ammonium, CH$_3$, MA$^+$, or formamidinium, FA$^+$) is located in the vertex of the face-centred cubic lattice, and the metal cation B (Pb$^{2+}$, Sn$^{2+}$, etc.) and halogen anion X (Cl$^-$, Br$^-$, or I$^-$, or a coexistence of several halogens) occupy the core and apex of the octahedra, respectively. The metal-halogen octahedra are joined together to form a stable three-dimensional network structure. The materials with such a structure have the following four features. Firstly, the materials possess excellent photoelectric properties, lower exciton binding energy, and high optical absorption coefficients (up to $10^4$ cm$^{-1}$) (Sun and Salim, 2014). Secondly, perovskite as the light-absorbing layer can absorb solar energy efficiently (Bagher et al., 2015). Thirdly, the materials possess a large dielectric constant and electrons and holes can be effectively transmitted and collected. Lastly, electrons and holes can be transmitted simultaneously and the transmission distance is up to 100 nm or more and even more than 1 μm (Green and Snaith, 2014)
These features lead to a high open-circuit voltage and a short-circuit current density if the materials are employed in solar cell devices. During exposure to sunlight, the perovskite layer firstly absorbs photons to produce excitons (electron-hole pairs). Due to the difference in the exciton binding energy of the perovskite materials, these excitons can form free carriers (free electrons and holes) to generate a current or can recombine into excitons. Due to the low carrier recombination probabilities of CH$_3$NH$_3$PbI$_3$ (MAPbI$_3$) and other perovskite materials and the higher carrier mobility, the diffusion distance and lifetime of the carrier are long. For example, the carrier diffusion distance is at least 100 nm for MAPbI$_3$ and longer than 1 μm for Cl$_x$ the longer diffusion distance and lifetime of carriers are the source of the superior performance of perovskite solar cells. (Green et al., 2014)

2.17.7 Graphene Solar Cells

Graphene is a flat, one-atom thick sheet of carbon which can be used as ultra-thin transparent conductive film for window electrodes in solar cells. Such conductive, transparent, and ultrathin graphene films obtained from exfoliated graphite oxide, followed by thermal reduction, have a thickness of about 10 nm and exhibit a high
conductivity, comparable to that of polycrystalline graphite, and a transparency of more than 70% over 1000–3000 nm. The graphene films can also be prepared via bottom-up construction of extremely large PAHs, nanographene molecules, followed by thermal fusion. To demonstrate how the transparent graphene films are potential window electrodes for optoelectronics a dye sensitized solid solar cell using the graphene film as anode and gold as cathode was fabricated. The efficiency of these non-optimized DSC is lower than traditional titania coating based solar cells, but there is large room for improvement of the device performance.

Figure (2.30) Illustration of solar cells based on graphene electrodes.
by, for example, further increasing the conductivity of the graphene films via the use of large graphene sheets. In general, however, the excellent properties of the obtained graphene film including high conductivity, good transparency in both the visible and near infrared regions, ultra-smooth surface with tunable wettability, and high chemical and thermal stabilities, render the graphene-based electrodes suitable as a very practicable option for future solar cells. Furthermore, simple processing enables inexpensive and large scale industrial manufacturing, another reason why the concept of using graphene electrodes is emerging as a very promising option for future optoelectronic devices. Free-standing graphene layers using the bandgap engineering approach recently developed may well have opened the route to a new generation of carbon-based PV cells. (Zhou et al., 2007)

Indeed, a significant 0.26 eV gap has been recently introduced into the electronic band structure. This carbon allotrope was first fabricated in 2004 by simple epitaxial graphene growth of its two-dimensional crystal on a silicon carbide substrate. Graphene is a densely packed single layer of carbon atoms, arranged in a hexagonal pattern like a honeycomb that forms a two-dimensional sheet. Electrons can move ballistically through graphene, even at room temperature, which means they can fly through the sheet like photons through a vacuum, undergoing none of the collisions with atoms that generate heat and limit the speed and size of silicon-based devices. The interaction between graphene and the substrate needs to be strong enough that a band-gap will be opened up but not so strong as to lose the important properties of graphene. By selecting the right substrate, therefore, this effect opens the route to the band-gap engineering of graphene, as different substrates have different potentials, and the strength of the interaction between the graphene and the substrate leads to different band-gap sizes. Incidentally, graphene-based cells would eliminate the problem of indium scarcity that may affect development of thin film photovoltaics. Indium is expensive and scarce and demand is increasing. The cost of indium may soon be irrelevant because geologists report that the earth’s supply of this element could be exhausted within just a few years. (Wang et al., 2008).
2.17.8 Dye-Sensitized Solar Cell (DSSC)

Dye Sensitized solar cells (DSSC), are a third generation photovoltaic (solar) cell that converts any visible light into electrical energy. This new class of advanced solar cell can be likened to artificial photosynthesis due to the way in which it mimics nature’s absorption of light energy. In contrast to the conventional systems where the semiconductor assume both the task of light absorption and charge carrier transport the two functions are separated here. Light is absorbed by a sensitizer, which is anchored to the surface of a wide band semiconductor. Charge separation takes place at the interface via photo-induced electron injection from the dye into the conduction band of the solid (Grätzel, 2003).

A charge separation process in a DSSC consists of the following steps:

(i) Photoanode absorbs incident solar energy. Upon absorption of photo energy, the electrons in the dye become exited from ground state to the excited state
(ii) Due to the difference in energy levels of the electronic states, electrons from the exited state are injected to the conduction band of the semiconductor. As a result the dye becomes oxidized.
(iii) The electrolyte, which is in contact with the dye, then donates electrons to the dye restoring it to the initial state
(iv) Electrolyte then diffuses towards the catalytic electrode where the reduction reaction takes place and electrolyte restores its initial state by accepting electrons from the external circuit.
(v) In addition to these forward charge transfer processes, backward charge transfer processes also occur in one complete cycle. These backward electron transfer processes drastically reduce the efficiency of DSSCs. These include the following:(a) transfer of electrons from the semiconductor to the oxidized dye,(b) recombination of injected electrons with the electrolyte (dark current),(c) transfer of electrons from the dye in its excited state to the dye in the ground state. (Umer et al., 2014)

Dye Sensitized solar cells (DSSC) were invented in 1991 by Professor Michael Graetzel and Dr Brian O'Regan at cole Polytechnique Fédérale de Lausanne (EPFL), Switzerland
and is often referred to as the Graetzel cell, we call it G Cell. DSSC is a disruptive technology that can be used to produce electricity in a wide range of light conditions, indoors and outdoors, enabling the user to convert both artificial and natural light into energy to power a broad range of electronic devices. A dye-sensitized solar cell DSSC, DSC or DYSC is a low-cost solar cell belonging to the group of thin film solar cells. It is based on a semiconductor formed between a photo-sensitized anode and an electrolyte, a photo electrochemical system. The DSSC has a number of attractive features; it is simple to make, using conventional roll-printing techniques, it is semi-flexible and semi-transparent which offers a variety of uses not applicable to glass-based systems, and most of the materials used are low cost. In practice it has proven difficult to eliminate a number of expensive materials, notably platinum and ruthenium, and the liquid electrolyte presents a serious challenge to making a cell suitable for use in all weather. Although its conversion efficiency is less than the best thin-film cells, in theory its price/performance ratio should be good enough to allow them to compete with fossil fuel electrical generation by achieving grid parity. (Tributsch, 2004).

Commercial applications, which were held up due to chemical stability problems, are forecast in the European Union Photovoltaic Roadmap to significantly contribute to renewable electricity generation by 2020. Solar cells made from the dye-adsorbed nanoporous TiO2 can drastically increase effective light absorption. By designing proper electrode thickness and sensitization dyes, DSCs are able to absorb most of the visible light. The current highest energy conversion efficiency is over 11%, and further increase of the efficiency is possible. DSC comprises a dye-sensitized nanoporous TiO2 electrode on transparent conductive oxide (TCO) electrode, electrolytes containing \( I^-/I_3^- \) redox couple filling the pore of the electrode, and a platinum counter electrode placed on the top of the TiO2 electrode. Fig. 1 shows the structure of the DSC, a SEM image of typical nanoporous TiO2 electrodes and the structure of a ruthenium (Ru) complex dye designed for DSCs. The nanoporous electrodes. (Soga, 2006)
2.17.9 Concentrator solar cells

Following the sun, a concentrating photovoltaic system (CPV) converts light energy into electrical energy in the same way that conventional photovoltaic technology does, but uses an advanced optical system to focus a large area of sunlight onto each cell for maximum efficiency. Different CPV designs exist, sometimes differentiated by the concentration factor, such as low-concentration (LCPV) and high concentration (HCPV). It uses lenses and curved mirrors to focus sunlight onto small, but highly efficient, multi-junction (MJ) solar cells. In addition, CPV systems often use solar trackers and sometimes a cooling system to further increase their efficiency. Concentrating photovoltaic systems work by converting solar light into electricity. Traditional rooftop solar modules rely on the same basic concept to generate electricity. CPV systems have an optical component, which “concentrates” significant amounts of sunlight onto “multi-junction” solar cells. Especially high concentrating photovoltaic (HCPV) systems have the potential to become competitive in the near future. They possess the highest efficiency of all existing PV technologies, and a smaller photovoltaic array also reduces
the balance of system costs. Currently, CPV is not used in the PV roof top segment and far less common than conventional PV systems. Concentrating photovoltaic (CPV) modules work in much the same way as traditional PV modules, except that they use optics to concentrate the sun onto solar cells that do not cover the entire module area. This concentration factor – in Semprius’ case over 1,100 times – dramatically reduces the amount of semiconductor needed (<0.1 percent) and opens up the potential to cost-effectively use very high performance multi-junction cells with efficiency levels. (Bagher et al., 2015)

The generation of electricity from solar energy varies morning to evening in a day, depending upon the intensity of light. More power can be extracted at noon when the intensity of light is at its peak. Moreover, the orientation of panel is also very important factor to taken into consideration. If the panel is mounted in such a way that it receives maximum power at noon, then the received power will be minimum in the morning and evening because of the radiation falling over solar panel. If panel is mounted perpendicular to light, it will generate maximum power as compared to other incident angels. So, it is desirable to fix the panel in such a way that it will face the sun for longer period or a sun-tracking mechanism should be designed for the panel. Tracking system is designed in such a way that it tracks the sun on a single axis (azimuth angle) or on two axes (azimuth and altitude angles). As electricity produced by PV module is directly related to the intensity of light radiation it is receiving, so in order to increase the efficiency of the system a concentrating technique may be a better solution. This would considerably decrease the cost of generation of electricity by PV panels. It has been found by Sungur C. that tracking system with multi-axes could generate 42.6% more energy than fixed panel system. One easy way to improve the performance of PV system is to use cost effective reflecting mirrors and light concentrators like concentrator photovoltaics (CPV). (Sungur, 2009).

Due to minimum cost and simplified assembly of reflecting mirrors, conventional technologies make low price manufacturing possible. In this generation, theoretical efficiency of a PV cell is said to be near 25% to 30% while a practical efficiency is around 17%. By cooling the panel through air or water, efficiency of the system can be increased to a greater value. Performance improvement of PV panel by means of all the
systems nearly involves the process of increasing the sun light radiation intensity over the panel, which in turn increases the output current accordingly and output voltage is somewhat increases. Another mean for improving output of PV module is using the concentrator or simple reflecting mirrors. Reflecting mirrors for performance improvement of PV module. Cooling solar panel is another way for performance enhancement. Precise overviews sun tracking, light reflection and panel cooling methods for performance enhancement are illustrated below:

1- Tracking of Sun:
Solar tracking is a very important method for enhancing the solar panels output. But truly, it has not become that much popular. Sun tracking is done in order to get the maximum amount of sun light. Experiments have shown that, it is a very simple and effective way for improving the yield of solar panel system by almost 20%. However, drawback of this system is that, during running, it dissipates some electric power which is itself produced by the PV panel. It requires very advanced machine and much trained personnel as well as maintaining employee on daily basis.

2- Concentrated and dispersed light reflection
Concentrated and dispersed light reflectors tend to reflect intense as well as focused sun light radiation but expends them approximately unvarying over the solar panel by means of dispersed light radiation. As the panel surface gets heated with extra light radiation, it needs fast cooling for better performance. Cooling of the panel could be performed either from downside or topside. In this design, to avoid extra cost system has been placed in a site where natural air could cool it.

3- Reflecting mirrors
Reflection of light through mirrors is the easiest and most effective way of light reflection. By reflecting light over the solar panel, output currents and nominal voltage increases, therefore, improves the performance of the PV panel system. After obtaining the field data, it was observed that improvement of output current by panel after using reflecting plane mirror was greater than the tracking of sun. Secondly, plane reflecting mirrors are very economical and easily available everywhere. (Bilal et al., 2016).
Figure (2.32) Solar cell concentrator (Reflecting mirrors) (Yupeng et al., 2012)
Figure (2.33) Solar cell concentrator (Fresnel lens)
(Yupeng et al., 2012)

Fig. (2.34) Photovoltaic technology status and prospects. (Nilofar et al., 2012)
Figure (2.35) Chart of Efficiencies for some solar cells
(Kaur and Singh, 2016; Martin et al., 2016)

2.17.10 Quantum Dot Solar Cells

A quantum dot solar cell is a solar cell design that uses quantum dots as the absorbing photovoltaic material. It attempts to replace bulk materials such as silicon, copper indium gallium selenide (CIGS) or CdTe. Quantum dots have bandgaps that are tunable across a wide range of energy levels by changing the dots’ size. In bulk materials the bandgap is fixed by the choice of material. This property makes quantum dots attractive for multi-junction solar cells, where a variety of materials are used to improve efficiency by harvesting multiple portions of the solar spectrum. Quantum dots are semiconducting particles that have been reduced below the size of the Exciton Bohr radius and due to quantum mechanics considerations, the electron energies that can exist within them
become finite, much alike energies in an atom. Quantum dots have been referred to as "artificial atoms". These energy levels are tuneable by changing their size, which in turn defines the bandgap. The dots can be grown over a range of sizes, allowing them to express a variety of bandgaps without changing the underlying material or construction techniques (Baskoutas and Terzis, 2006)

In typical wet chemistry preparations, the tuning is accomplished by varying the synthesis duration or temperature. The ability to tune the bandgap makes quantum dots desirable for solar cells. Single junction implementations using lead sulfide (PbS) CQDs have bandgaps that can be tuned into the far infrared, frequencies that are typically difficult to achieve with traditional. Half of the solar energy reaching the Earth is in the infrared, most in the near infrared. Moreover, CQDs offer easy synthesis and preparation. While suspended in a colloidal liquid form they can be easily handled throughout production, with a fume hood as the most complex equipment needed. CQDs are typically synthesized in small batches, but can be mass-produced. The dots can be distributed on a substrate by spin coating, either by hand or in an automated process. Large-scale production could use spray-on or roll-printing systems, dramatically reducing module construction costs.

Figure (2.36) Quantum dot solar cell   (Credit: Adapted from J phy. Chm. Lett)
Table (2.2) Advantages, disadvantages and efficiencies of types of silicon solar cells and concentrated PV cell

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>efficiency</td>
<td>~20%</td>
<td>~15%</td>
<td>~7-10%</td>
<td>~41%</td>
</tr>
<tr>
<td>Advantages</td>
<td>High efficiency rate; optimised for commercial use; high life time value</td>
<td>Lower price</td>
<td>Relatively low costs; easy to produce &amp; flexible</td>
<td>Very high performance &amp; efficiency rate</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Expensive</td>
<td>Sensitive to high temperatures; lower lifespan &amp; slightly less space efficiency</td>
<td>shorter warranties &amp; lifespan</td>
<td>Solar tracker &amp; cooling system needed (to reach high efficiency rate)</td>
</tr>
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2.18 Physical and chemical properties of the materials used in fabrication the solar cell

2.18.1 Carbon

Carbon (C), nonmetallic chemical element in Group 14 (IVA) of the periodic table. Although widely distributed in nature, carbon is not particularly plentiful—it makes up only about 0.025 percent of Earth’s crust—yet it forms more compounds than all the other elements combined. In 1961 the isotope carbon-12 was selected to replace oxygen as the standard relative to which the atomic weights of all the other elements are
measured. Carbon-14, which is radioactive, is the isotope used in radiocarbon dating and radionlabeling. Elemental carbon exists in several forms, each of which has its own physical characteristics. Two of its well-defined forms, diamond and graphite, are crystalline in structure, but they differ in physical properties because the arrangements of the atoms in their structures are dissimilar. A third form, called fullerene, consists of a variety of molecules. Pure diamond is the hardest naturally occurring substance known and is a poor conductor of electricity. Graphite, on the other hand, is a soft slippery solid that is a good conductor of both heat and electricity. Carbon has a ground-state electron configuration of 1s^22s^22p^2, the four outer electrons are valence electrons. The band gap of diamond is 5.47 eV it is indirect band gap. (Kasap and Capper, 2006). Carbon nanotubes, a fourth allotrope of carbon, can be envisioned as sheets of graphite rolled into tubes with hemispherical fullerene caps on the ends. A single sheet of graphite, known as graphene, can be rolled in different directions to produce nanotubes with different configurations display different materials properties. Carbon nanotubes also are being considered as possible conductors of electricity in advanced nanoelectronic devices. (Donald et al., 2006).

2.18.2 Silicon

Silicon is a chemical element with symbol Si and atomic number 14. A hard and brittle crystalline solid with a blue-grey metallic lustre, a tetravalent it metalloid and semiconductor. It is a member of group 14 in the periodic table. Single. Monocrystalline silicon of such purity is usually produced by the Czochralski process, is used to produce silicon wafers used in the semiconductor industry, in electronics, and in some high-cost and high efficiency photovoltaic applications. It never occurs free in nature, but in combination with oxygen forming oxides and silicates. (David, 2005).

Pure silicon is an intrinsic semiconductor, which means that unlike metals, it conducts electron holes and electrons released from atoms by heat; silicon's electrical conductivity increases with higher temperatures. Pure silicon has too low a conductivity to be used as a circuit element in electronics. In practice, pure silicon is doped with small concentrations of certain other elements, which greatly increase its conductivity and adjust its electrical response by controlling the number and charge (positive or negative).
of activated carriers. Such control is necessary for transistors, solar cells, semiconductor detectors, and other semiconductor devices used in the computer industry and other technical applications. In silicon photonics, silicon can be used as a continuous wave Raman laser medium to produce coherent light. In common integrated circuits, a wafer of monocrystalline silicon serves as a mechanical support for the circuits, which are created by doping and insulated from each other by thin layers of silicon oxide, an insulator that is easily produced by exposing the element to oxygen under the proper conditions. A silicon atom has fourteen electrons. In the ground state, they are arranged in the electron configuration $1s^22s^22p^63s^23p^2$ and atomic radius is 0.132 nm. Of these, four are valence electrons, occupying the 3s orbital and two of the 3p orbitals. Silicon has the diamond cubic crystal structure with a lattice parameter of 0.543 nm. The nearest neighbor distance is 0.235 nm. The diamond cubic crystal structure has an FCC lattice with a basis of two silicon atoms. (Dekker et al., 2008).

The types of silicon are:
1- Monocrystalline also called single-crystal silicon. 2- Amorphous silicon 3- Polycrystalline silicon.

![Diamond cubic crystal structure of silicon](image)

Figure (3.1) The diamond cubic crystal structure of silicon

Silicon is transparent to infrared light with wavelengths above about 1 micrometres. .
Magnesium is a chemical element with symbol Mg and atomic number 12. It is a shiny gray solid which bears a close physical resemblance to the other five elements in the second column (group 2, or alkaline earth metals) of the periodic table. The electronic configuration of Mg is $1s^22s^22p^63s^2$. Magnesium is a shiny silver metal, with an moderately high strength to weight ratio. Atoms are held in a metallic structure. Magnesium is a good conductor of heat and electricity. Magnesium is the eighth most abundant element in the Earth's crust and the fourth most common element in the Earth (after iron, oxygen and silicon), making up 13% of the planet's mass and a large fraction of the planet's mantle. It is the third most abundant element dissolved in seawater, after sodium and chlorine. The crystal structure of Magnesium is simple hexagonal. (David, 2005).

Aluminum is the most abundant metal to be found in the earth’s crust (8.1%), but is never found free in nature. In addition to the minerals mentioned above, it is found in feldspars, granite, and in many other common minerals. Twenty-two isotopes and isomers are known. Natural aluminium is made of one isotope, $^{27}$Al. Pure aluminium, a silvery-white metal, possesses many desirable characteristics. It is light, nontoxic, has a pleasing appearance, can easily be formed, machined, or cast, has a high thermal conductivity, and has excellent corrosion resistance. It is nonmagnetic and nonsparking, stands second among metals in the scale of malleability, and sixth in ductility. It is extensively used for kitchen utensils, outside
building decoration, and in thousands of industrial applications where a strong, light, easily constructed material is needed. Although its electrical conductivity is only about 60% that of copper, it is used in electrical transmission lines because of its light weight. Pure aluminium is soft and lacks strength, but it can be alloyed with small amounts of copper, magnesium, silicon, manganese, and other elements to impart a variety of useful properties. These alloys are of vital importance in the construction of modern aircraft and rockets. The electronic configuration of Al is $1s^22s^22p^63s^23p^1$. The crystal structure of Aluminium is Face-centered Cubic. Aluminium, evaporated in a vacuum, forms a highly reflective coating for both visible light and radiant heat. These coatings soon form a thin layer of the protective oxide and do not deteriorate as do silver coatings. They have found application in coatings for telescope mirrors, in making decorative paper, packages, toys, and in many other uses. The compounds of greatest importance are aluminium oxide, the sulfate, and the soluble sulfate with potassium. The oxide, alumina, occurs naturally as ruby, sapphire, corundum, and emery, and is used in glass making and refractories. Synthetic ruby and sapphire have found application in the construction of lasers for producing coherent light. (David, 2005).

2.18.5 Sulphur

Sulfur or Sulphur is a chemical element with symbol S and atomic number 16. It is abundant, multivalent, and non-metallic. Elemental sulphur is a bright yellow crystalline solid at room temperature. Sulphur is insoluble in water; it is not ever wetted by it. Sulphur is highly soluble in carbon disulphide and sparingly soluble alcohol and ether. It has a low melting point (114°C). It occurs in a number of allotropic forms a two of which, the rhombic and monoclinic, are crystalline.

Sulfur is the tenth most common element by mass in the universe, and the fifth most common on Earth. Elemental sulfur is non-toxic. The electronic configuration of S is $1s^22s^22p^63s^23p^4$ and the crystal structure is Face-centered orthorhombic.

2.18.6 Zinc

Zinc is a chemical element with symbol Zn and atomic number 30. It is the first element in group 12 of the periodic table. In some respects zinc is chemically similar to magnesium; both elements exhibit only one normal oxidation state (+2), and the Zn$^{2+}$ and Mg$^{2+}$ ions are of similar size. Zinc makes up about 0.0075% of Earth's crust.
making it the 24th most abundant element. Zinc is a bluish-white, lustrous, diamagnetic metal, though most common commercial grades of the metal have a dull finish. It has a hexagonal crystal structure, with a distorted form of hexagonal close packing. Zinc has an electron configuration of [Ar]3d^{10}4s^{2} and is a member of the group 12 of the periodic table. And it exhibits simple hexagonal crystal structure. It is a moderately reactive metal and strong reducing agent. (David, 2005).

2.18.7 Copper

Copper is a chemical element with symbol Cu and atomic number 29. It is a soft, malleable, and ductile metal with very high thermal and electrical conductivity. A freshly exposed surface of pure copper has a reddish-orange color, and is present in the Earth's crust in a proportion of about 50 parts per million (ppm). Copper is used as a conductor of heat and electricity, as a building material, and as a constituent of various metal alloys, such as sterling silver used in jewelry, cupronickel used to make marine hardware and coins, and constantan used in strain gauges and thermocouples for temperature measurement. The crystal structure of copper is Face-centered cubic. The electronic configuration of Cu is [Ar] 3d^{10} 4s^{1} (David, 2005).

2.18.8 Cadmium

Cadmium is a chemical element with symbol Cd and atomic number 48. This soft, bluish-white metal is chemically similar to the two other stable metals in group 12, namely zinc and mercury. Cadmium is a soft, malleable, ductile, bluish white divalent metal. The average concentration of cadmium in Earth's crust is between 0.1 and 0.5 parts per million (ppm). Cadmium use is generally decreasing because it is toxic. One of its few new uses is cadmium telluride solar panels. The crystal structure of Cd is Simple hexagonal.
2.18.9 Potassium Chlorate (KClO3)
Potassium chlorate is a compound containing potassium, chlorine and oxygen atoms, with the molecular formula KClO₃. In its pure form, it is a white crystalline substance. It is the most common chlorate in industrial use. Among of its usages, is used as an oxidizing agent, and to prepare oxygen.

2.18.10 Coumarin 500 dye
7-Ethylamino-4-trifluormethylcoumarin (C₁₂H₁₀NO₂F₃). It is appearance in yellow crystalline solid. (Ulrich, 2000).

2.18.11 Indium tin oxide (ITO)
Indium tin oxide (ITO) is one of the most widely used transparent conducting oxides. The key properties for high-quality TCOs are high optical transmission (high band gap for window materials), low electrical resistivity and high carrier mobility, low surface roughness (for most devices), good thermal and chemical stability, good crystallinity (for most devices), adhesion and hardness, and low processing cost. Typical processes used to fabricate TCOs include chemical and physical vapour deposition, sputtering, laser ablation, spraying, and solution growth (e.g., chemical bath deposition). ITO can be deposited as a thin film and it is a heavily doped n-type semiconductor with a large band gap of around 4 eV. Because of the band gap, it is mostly transparent in the visible part of the spectrum and its extinction coefficient, k, in this wavelength range is zero. In the ultraviolet (UV), it is opaque, so that k is non-zero in the UV spectral range, because of band-to-band absorption (a UV photon can excite an electron from the valence band to the conduction band). It is also opaque in the near infrared (NIR) and infrared (IR), because of free carrier absorption (an infrared photon can excite an electron from near the bottom of the conduction band to higher within the conduction band). In this wavelength range k is non-zero, and reaches its maximum value in the IR regime, similar to the behavior of k for metals. This is mainly due to ITO’s highly degenerate behavior as an n-type semiconductor with a large band gap of around 3.5 to 4.3 eV. (Ginley et al, 2010; Dutra, 2017)

2.19 Previous studies
Different attempts were made to fabricate new solar cell types. In this section some of these attempts are exhibited.

2.19.1 The Effect of different Dyes on the Efficiency of polymer solar cell
The study made by Gasim and others take care of the effect of changing dyes on the performances of polymer solar cells (Gasim et al., 2014)

Polymer solar cells are one of the promising alternative energies which can be easily manufactured with low cost. In this work polymer cells with different thicknesses and three different types of organic dyes (Rhodamine 6G, Coumarin 500 and Dibenzocyanin 45) are used in fabrication. The effect of the concentration of different organic dye on various electrical and optical properties of the samples produced has been studied. It was
found that when the conjugate polymer layer deposition on the slides at low speeds by spin coating technique (increasing the thickness of the conjugate polymer layer), results gave a recognized higher efficiency in the tested cell. The use of the organic dye (DDTTCl) led to improve in efficiency and absorption coefficient of light in the samples used. In addition, the optical absorption spectra were recorded for those samples with a UV-VIS spectrophotometer (model: UV mini-1240) within the wavelength range of 200–800 nm, at room temperature. The samples show variations in absorption coefficient directly depending on the type of organic dye used as well as the concentration of conjugate polymer. The short-circuit current, open circuit voltage and the fill factor of each sample have been calculated. The efficiency was found in the range of 10.28–1.744% for designed samples.

2.19.2 The effect of different concentrations of CuO on solar cell performance

In this work (Mokhtar et al., 2017) studied the effect of the concentration of CuO on the performance of solar cell. CuO solar cells fabricated from polymer, with different CuO concentrations ranged from (0.3 to 0.25) mg/mL were prepared. It was found that increasing CuO concentration increases efficiency. This can be explained on the basis of the relation between current and concentration of CuO. In this work it is found that there is a sudden increase in the efficiency of the cell at concentrations of (0.28 and 0.25) this is explained by the same mechanism of Mott Insulator of super conductivity. It assumes the existence of narrow energy band in the energy gap; thus the shift of Fermi Level affects the efficiency. The efficiency of CuO solar cell can be increased by changing concentration of CuO. One can also change the efficiency by controlling the Fermi level position also.

2.19.3 The determination of energy gap and effect of temperature on the absorption and transmittance spectrum on photoelectrodyne

Mohammed and some researchers tried to see how temperature change affects some of the optical properties of dyes. (Mohammed et al., 2015)
In this study the optical properties of the dye Roselle anthocyanins shows high absorption to visible spectrum because of concentration of anthocyanin in Roselle calyces. Its absorption to sun light is almost constant which is an indication of chemical stability. The absorption spectrum of the anthocyanin dye dissolved in methanol shows $\lambda_{\text{max}}$ (283 nm) in the UV region, while $\lambda_{\text{max}}$ (545 nm) in the VIS range. The corresponding energy levels are 4.36 and 2.25 eV respectively. The absorption spectrum of fresh Roselle crude shows in the visible region. The energy gap of Roselle is 2.06, while that of titanium dioxide is 4.125. These values agree with the standard values. The response of optical absorption to temperature shows stability at ambient temperature, while absorption decreases as temperature increases above ambient temperature. The thermal properties of the Roselle anthocyanin dye indicates that its absorption property, i.e., the ability of atoms to trap visible photons, is stable and is not affected by temperature at ordinary ambient temperature. But at higher temperatures the absorption decreases. It shows also almost temperature absorption to direct sun light thus indicating high chemical stability. The optical property of the Roselle anthocyanin dye shows high efficiency to absorb visible light. This may have a direct impact on increasing the efficiency of the solar cell, as long as the function of the dye is to trap visible light.

2.19.4 The effect of different concentrations of ZnO on solar cell performance

Mokhtar, K.M. and others studied the effect of ZnO concentration on solar cell performance (Mokhtar et al., 2017).

In this work, ZnO solar cells fabricated from polymer, with different ZnO concentrations ranged from (0.3 to 0.25) mg/mL were prepared. The performance of these cells show increases in the efficiency when the concentration of ZnO increases. This agrees with the theoretical relations. However some results show efficiency increase, when concentration decreases. This can be explained by a mechanism similar to that of Mott insulator, due to the change of position of the Fermi level. The solar cells fabricated from ZnO show change of efficiency due to the change of ZnO
concentration. This change causes two effects, one of them is change of free carriers and change of the position of Fermi level.

**2.19.5 The relationship between energy gap and efficiency of dye solar cells**

Recently attention was payed to polymer and dye sensitized solar cells. These cells were cheap and can be easily fabricated. This motivated Ali, I. A. (in Sudan University of Science & Technology-College of Science- Department of Physics) and others to see how the energy gap affect the efficiency. (Ali et al., 2016). In this work dye sensitized solar cells made from: Ecrrhrom Black T, DDTTC, Rohadamin B, and Coumarin 500, with Al and ITO electrodes were fabricated. The energy gap of these dyes were found using UV Spectrometer. The energy gap for: Ecrrhrom Black T, DDTTC, Rohadamin B, and Coumarin 500 ; were found 2.16 eV , 2.20 eV , 3.27 eV and 3.60 respectively . The V- I characteristics for these cells and their performance were also found. The efficiency: Ecrrhrom Black T, DDTTC, Rohadamin B, Coumarin 500 were found 1.66, 1.62, 1.49 and 1.31. It is realized that; the efficiency increased when energy gap decreased. In conclusions, this work shows that the energy gap of the dyes used in dye sensitized solar cell affect the performance and efficiency of the solar cell.

**2.19.6 The relationship between atomic number and efficiency of dye solar cell**

The efficiency of dye solar cells was found to be related to the atomic number as pointed out by (Ali et al., 2016). In this work the effect of changing the anode of polymer solar cell on their performance was experimentally investigated .The cells were fabricated from ITO which act as a cathode beside MEH PPV , Ecrrhrom Black T and Rohadamin B dye. The anodes which are AL, G, AU with atomic number 13 , 47 and 79 were used . It was found that the efficiency of the solar cell of AL, GL, and AU electrode for Ecrrhrom dye are 1.66, 1.59, and 1.58, respectively. The efficiency for Rohadamin , Ecrrhrom Black T dye are 1.49, 1.48 and 1.46, respectively. These results shows clearly that the efficiency increases as the atomic number decreases this conforms with the fact that energy gap increase with the atomic number. In conclusion, the electrode material affect dye polymer solar cell performance through the atomic number of the electrode.
2.19.7: Energy gaps, donor and accepter levels for polymer solar cells doped with different dyes

In the work done by Mohamed, A. A. and others (Mohamed et al., 2016), the energy levels and energy gaps of polymer solar cells values were found when they are doped with Coumarin, Lawsonia, Rohdamin B, Blue 8GX, Roselle, DDTTC and Ero-Chrom black, by means of the values of absorption and transmission spectra, beside values of absorption coefficient- intensity relations of them. The results obtained show that the absorption spectra which relates intensity and emitted wavelengths for them gives the values of donor and acceptor levels which are 5.07, 4.41, 5.08, 5.12, 4.57, 4.88 and 5.54 eV, respectively 2.43, 2.25, 2.45, 2.84, 2.32, 2.41 and 2.33 eV respectively. The transmission spectra for Coumarin, Lawsonia, Rohdamin B, Blue 8GX, Roselle, DDTTC and Ero-Chrom black is closely related to their energy gaps which were found to be 1.17, 3.58, 1.10, 1.08, 3.06, 3.52 and 1.11 eV. These values are in conformity with the results obtained by the absorption coefficient - intensity relations which predicts the energy gaps 3.55, 3.30, 3.27, 3.15, 3.08, 2.94 and 2.59 eV which are in agreement with the standard values. In conclusions, the application of conducting polymers to optoelectronic devices such as solar cell. Dyes Structure showed high optical absorption in the range of (200 to 537) nm. To increase power conversion efficiency, structures of the solar cells should be optimized.

2.19.8 The effect of changing of mass density of impurities added to TiO2-MEH on current and energy gap values

Elmahdi, T. M with others studied the effect of changing of mass density of impurities added to TiO2-M EH on current and energy gap values. (Elmahdi et al., 2017).

In this work, TiO2-MEH thin film has been grown onto glass substrate at room temperature by spin coating and doped with CaSO4, CuCO3 and La2O3. The current – voltage relation for the four samples were studied. It was found that at a certain voltage the current decreases as the density increases. This may be due to the fact that the density increasing, increases resistance and decreases current. The energy gap is also shown to be affected by the density. When the impurities were added the increase of free charge carriers causes the Fermi level to move and jump from the energy gap 2.216 to 3.721 eV.
Then upon increasing the mass density to be 2.69, 4.35 and 6.51 g/cm³ the energy gap decreases to be 3.721, 3.295 and 2.15 respectively. This decreasing may be related to the fact that, according to tight binding approximation, the density increases, increases the width of energy band, which in turn decreases the energy gap. The TiO₂-MEH binary layer electric characteristics are affected by different mass density of impurities. The mass density increasing; decreases current and energy gap values.
Chapter Three
Materials and Methods

3.1 Introduction

The equipments and the materials used in this work, are mentioned in this chapter. The experimental procedures used are also exhibited.

3.2 Materials:

The materials used in this work are: Potassium Chlorate ($\text{KClO}_3$), Coumarin 500 dye, deionized water, ITO glass (Indium Tin Oxide), nitric acid ($\text{HNO}_3$) and sulfuric acid ($\text{H}_2\text{SO}_4$).

3.3 Methods

3.3.1 Solar cell samples fabrication

5.0g of (graphite (99.995% purity) or Silicon Oxide) was slowly added to a mixture of fuming nitric acid (25mℓ) and sulfuric acid (50mℓ). After cooling the mixture down to 5°C in an ice bath, 25.0 g of potassium chlorate was slowly added to the solution while stirring. Since a lot of heat was produced while adding potassium chlorate to the mixture, special care was taken during this step. The solution was heated up to 70°C for 24 hours in an oven and then placed in the air for 3 days. Most graphite precipitated at the bottom but some reacted with carbons were floating. The floating carbon materials were transferred into deionized water (1ℓ) . After stirring it for 1 hour, the solution was immediately filtrated and the sample was dried. Then six samples were prepared by doping Silicon – as a host material- with (Zn, Mg, Al, S ,Cd and Cu) , and other six samples were prepared by doping Carbon- as a host material- with the same elements i.e.(Zn, Mg, Al, S, Cd and Cu). For each of the 12 samples, a small amount was put onto the conductive side of an Indium Tin Oxide (ITO) glass and uniformly distributed forming a thin layer using a glass rod. After the thin layer dried, drops of Coumarin 500 dye were added on it. Another Indium Tin Oxide glass was coated with graphite using a pencil on the conductive side. The two conductive sides of Indium Tin Oxide glasses facing each other were fixed using two clips. So, there were 12 solar cells to be
characterized, 6 silicon solar cells and 6 carbon solar cells. The two conductive sides represent the two electrodes of the solar cells, as shown in Figure (3.5)

![Diagram of the solar cell structure (Carbon or Silicon samples)](image)

**Figure (3.5): The structure of the solar cell (Carbon or Silicon samples)**

### 3.3.2 Solar cell characterization

#### 3.3.2.1 Apparatus:

- microvolt-DMM- voltmeter, KETHLEY-USA- 177 DC,1 electrometer- ammeter, KETHLEY-USA- 642 DC, 12 V, 50/100 W 450 64 , Rheostat ( Albert van der perk nV Rollerd-No-464151-27Ω-5.2A). halogen lamp housing (light source of intensity 0.55mW.cm$^2$), connecting wires.

#### 3.3.2.2 Experimental Setup:

- The solar cell into the plug-in board was plugged, and the upper negative pole to the lower positive pole were connected using two bridging plugs (series connection of the solar cells).
- The potentiometer as a variable resistor was plugged, and connected it to the solar battery using bridging plugs.
- The ammeter was connected in series with the solar battery and the variable resistor. The measuring range was selected (100 -10$^{-12}$AC- DC) Current.
The micro voltmeter was connected in parallel to the solar cell. The measuring range was selected (1000 -10^6 AV- DV) Voltage.

The source of light was connected to the transformer, and aligned so that the solar cell is uniformly irradiated. The experimental setup is shown in the Fig (3.6)

Fig (3.6): The experimental setup

3.3.2.3 Carrying out of the experiment:

The circuit was closed, first shorting the variable resistor with an additional bridging plug, in this case the rheostat resistance R= 0 Ω so that the short circuit current I_sc was determined, and the distance of the halogen lamp was fixed throughout the experiment.
➢ Then the circuit was interrupted, and measured the open-circuit voltage. \( V_{oc} \) in case the load resistance (rheostat) was infinite \( R = \infty \) and the current \( I = 0 \)

➢ The shorting bridging plug was removed, and increasing the terminal voltage or decreasing the current, respectively, step by step by changing the load resistance. For each step the current and the voltage were read and recorded.

Figure (3.7) shows a photograph of Shimadzu spectrophotometer which measures absorbance, emission and permeability. The device components are: light source – a cell sample – uniform wavelength – Scout – Screen. The working principle of the device. Each of the articles has a characteristic absorption of a specific wavelength. Any material have a certain extent of absorption to unchangeable but the material properties change works on the principle Ber lambert based on assumptions:

* Absorbance is directly proportional to the concentration.

* Absorbance is directly proportional to the length of the optical path within the sample.
Figure (3.7) A photograph of shimadzu spectrophotometer that was used in optical absorption measurement
Fig (3.8) Carbolite oven

Chapter Four
Results and Discussion

4.1 Introduction

This chapter is concerned with the experimental results of silicon and carbon doped with some minerals. These results are displayed graphically. The discussion which analyzes the results is also presented here.

4.2 Results

In this section the optical and electrical characteristics of Si and C samples doped with (Zn, Mg, Al, S, Cd and Cu) are exhibited here in tables and graphs as shown below.

![Absorption versus wavelength for all samples of Silicon doped with metals](attachment:image.png)
Figure (4.2) Absorption coefficient versus photon energy for all samples of Silicon doped with metals.
Figure (4.3) Energy gaps for all samples of Silicon doped with metals

For each sample:
- Sample 1: $E_g = 5.920$ eV
- Sample 2: $E_g = 6.147$ eV
- Sample 3: $E_g = 5.805$ eV
- Sample 4: $E_g = 6.235$ eV
- Sample 5: $E_g = 5.107$ eV
- Sample 6: $E_g = 5.184$ eV
Figure (4.4) Absorption versus wavelength for all samples of Carbon doped with metals
Figure (4.5) Absorption coefficient versus photon energy for all samples of Carbon doped with metals
Figure (4.6) Energy gaps for all samples of Carbon doped with metals
Table (4.1) Relation between current I and voltage V for sample 1

(Silicon doped with Zn)

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.98549</td>
<td>0.0000</td>
</tr>
<tr>
<td>19.67199</td>
<td>0.01994</td>
</tr>
<tr>
<td>19.46299</td>
<td>0.03794</td>
</tr>
<tr>
<td>19.35849</td>
<td>0.0502</td>
</tr>
<tr>
<td>19.14949</td>
<td>0.06145</td>
</tr>
<tr>
<td>18.94049</td>
<td>0.07547</td>
</tr>
<tr>
<td>17.69231</td>
<td>0.09398</td>
</tr>
<tr>
<td>13.48331</td>
<td>0.11124</td>
</tr>
<tr>
<td>2.35994</td>
<td>0.12</td>
</tr>
<tr>
<td>0.00000</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Figure (4.7) Relation between current I and voltage V for sample 1

$I_{sc} = 19.32$ mA

$I_{max} = 16.56$ mA

$V_{max} = 0.105$ V

$V_{oc} = 0.1202$ V

$FF = 0.75$

$\eta = 0.028\%$

$J_{sc} = 3.09$ mA.cm$^{-2}$
(Silicon doped with Zn)

Table (4. 2) Relation between current I and voltage V for sample 2

(Silicon doped with Mg)

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.25E-4</td>
<td>21.09347</td>
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<tr>
<td>0.01711</td>
<td>21.09347</td>
</tr>
<tr>
<td>0.02303</td>
<td>20.99971</td>
</tr>
<tr>
<td>0.03327</td>
<td>21.13759</td>
</tr>
<tr>
<td>0.04622</td>
<td>21.36923</td>
</tr>
<tr>
<td>0.05535</td>
<td>21.41335</td>
</tr>
<tr>
<td>0.06573</td>
<td>21.27547</td>
</tr>
<tr>
<td>0.07949</td>
<td>18.94804</td>
</tr>
<tr>
<td>0.08925</td>
<td>13.37765</td>
</tr>
<tr>
<td>0.0955</td>
<td>0.00319</td>
</tr>
</tbody>
</table>

$I_{sc} = 21.17$ mA  
$I_{max} = 18.64$ mA  
$V_{max} = 0.082$ V  
$V_{oc} = 0.096$ V  
$FF = 0.75$  
$\eta = 0.025\%$  
$J_{sc} = 3.39$ mA.cm$^{-2}$
Figure (4.8) Relation between current I and voltage V for sample 2

(Silicon doped with Mg)

Table (4.3) Relation between current I and voltage V for sample 3

(Silicon doped with Al)

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.83019</td>
<td>0.0031</td>
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<tr>
<td>49.90566</td>
<td>0.01698</td>
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<tr>
<td>49.26415</td>
<td>0.02898</td>
</tr>
<tr>
<td>48.96226</td>
<td>0.03822</td>
</tr>
<tr>
<td>49.73585</td>
<td>0.04909</td>
</tr>
<tr>
<td>49.90566</td>
<td>0.05995</td>
</tr>
<tr>
<td>49.73585</td>
<td>0.07173</td>
</tr>
<tr>
<td>47.71698</td>
<td>0.08929</td>
</tr>
<tr>
<td>27.71698</td>
<td>0.10269</td>
</tr>
<tr>
<td>0.09434</td>
<td>0.11286</td>
</tr>
</tbody>
</table>

$I_{sc} = 49.95$ mA  
$I_{max} = 43.18$ mA  
$V_{max} = 0.095$ V  
$V_{oc} = 0.113$ V  
$FF = 0.73$  
$\eta = 0.065\%$  
$J_{sc} = 7.99$ mA cm$^{-2}$  
$V_{sc} = 0.113$ V
Figure (4. 9)nt I and voltage for sample 3

(Silicon doped with Al)

Table (4.4) Relation between current I and voltage V for sample 4

(Silicon doped with S)

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.51959</td>
<td>0.13316</td>
</tr>
<tr>
<td>3.98113</td>
<td>0.13144</td>
</tr>
<tr>
<td>9.49347</td>
<td>0.12918</td>
</tr>
<tr>
<td>20.08708</td>
<td>0.12093</td>
</tr>
<tr>
<td>32.19594</td>
<td>0.11069</td>
</tr>
<tr>
<td>37.70827</td>
<td>0.09107</td>
</tr>
<tr>
<td>39.98113</td>
<td>0.06863</td>
</tr>
<tr>
<td>41.06531</td>
<td>0.0345</td>
</tr>
<tr>
<td>41.60087</td>
<td>0.000000000E-4</td>
</tr>
</tbody>
</table>

Relation between current I and voltage V for sample 4

$I_{sc} = 41.02 \text{ mA}$

$I_{max} = 32.16 \text{ mA}$

$FF = 0.64$

$\eta = 0.056 \text{ %}$

$J_{sc} = 6.6 \text{ mA.cm}^{-2}$

$V_{max} = 0.108 \text{ V}$

$V_{oc} = 0.133 \text{ V}$
Figure (4.10)4

(Silicon doped with S)

Table (4.5) Relation between current I and voltage for sample 5

(Silicon doped with Cd)

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>Voltage (V)</th>
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</thead>
<tbody>
<tr>
<td>55.83019</td>
<td>0.0016</td>
</tr>
<tr>
<td>55.5283</td>
<td>0.02036</td>
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<tr>
<td>55.0566</td>
<td>0.03338</td>
</tr>
<tr>
<td>56.5</td>
<td>0.049</td>
</tr>
<tr>
<td>55.83019</td>
<td>0.06835</td>
</tr>
<tr>
<td>52.09434</td>
<td>0.08263</td>
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<tr>
<td>36.32075</td>
<td>0.09778</td>
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</table>
Figure (4.11) Relation between current I and voltage V for sample 5
(Silicon doped with Cd)

Table (4.6) Relation between current I and voltage for sample 6
(Silicon doped with Cu)

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>Voltage (V)</th>
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<tbody>
<tr>
<td>17.31736</td>
<td>8.87183E-4</td>
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<tr>
<td>17.41115</td>
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<td>17.04704</td>
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<td>16.54501</td>
<td>0.03128</td>
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<td>14.8566</td>
<td>0.03885</td>
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<td>12.35849</td>
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<td>9.54717</td>
<td>0.0436</td>
</tr>
<tr>
<td>5.98491</td>
<td>0.04408</td>
</tr>
<tr>
<td>0.9283</td>
<td>0.04461</td>
</tr>
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</table>
Figure (4.12) Relation between current I and voltage V for sample 6

(Silicon doped with Cu)

Table (4.7) Relation between current I and voltage V for Sample 7

(Carbon doped with Zn)

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>Voltage (V)</th>
</tr>
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<tbody>
<tr>
<td>37.73803</td>
<td>7.32388E-4</td>
</tr>
<tr>
<td>37.83672</td>
<td>0.01441</td>
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<td>37.69811</td>
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<td>30.58273</td>
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<tr>
<td>13.12627</td>
<td>0.04569</td>
</tr>
<tr>
<td>0</td>
<td>0.04695</td>
</tr>
</tbody>
</table>

$I_{sc} = 37.53$ mA
$I_{max} = 30.27$ mA
$V_{max} = 0.042$ V
$V_{sc} = 0.047$ V
$FF = 0.72$
$\eta = 0.0203\%$
$J_{sc} = 6$ mA.cm$^{-2}$
Figure (4.13) Relation between current I and voltage V for sample 7

(Carbon doped with Zn)

Table (4.8) Relation between current I and voltage for sample 8

(Carbon doped with Mg)

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.33159</td>
<td>0.00102</td>
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<tr>
<td>15.20819</td>
<td>0.01061</td>
</tr>
<tr>
<td>15.20819</td>
<td>0.01722</td>
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<tr>
<td>15.08549</td>
<td>0.023</td>
</tr>
<tr>
<td>15.118</td>
<td>0.02784</td>
</tr>
</tbody>
</table>

\[ I_{sc} = 15.29 \, mA \]
\[ I_{max} = 12.23 \, mA \]
\[ V_{max} = 0.045 \, V \]
\[ V_{oc} = 0.056 \, V \]
\[ FF = 0.64 \]
\[ \eta = 0.009 \, \% \]
\[ J_{sc} = 2.45 \, mA/cm^2 \]
Figure (4.14) Relation between current I and voltage V for sample 8

(Carbon doped with Mg)

Table (4.9) Relation between current I and voltage for sample 9

(Carbon doped with Al)
Figure (4.15) Relation between current I and voltage V for sample 9
(Carbon doped with Al)

Table (4.10) Relation between current I and voltage V for sample 10
(Carbon doped with S)

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>Voltage (V)</th>
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<tr>
<td>16.5016</td>
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<tr>
<td>16.59536</td>
<td>0.13391</td>
</tr>
<tr>
<td>16.63948</td>
<td>0.53823</td>
</tr>
<tr>
<td>16.31959</td>
<td>0.88939</td>
</tr>
<tr>
<td>15.91147</td>
<td>1.2137</td>
</tr>
<tr>
<td>14.90769</td>
<td>1.50687</td>
</tr>
<tr>
<td>12.71263</td>
<td>1.72917</td>
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<td>9.06154</td>
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<tr>
<td></td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>1.96</td>
</tr>
</tbody>
</table>

$I_{sc} = 16.28$ mA
$I_{max} = 13.67$ mA
$V_{max} = 1.713$ V
$V_{oc} = 1.9775$ V
$FF = 0.73$
$\eta = 0.375\%$
$J_{sc} = 2.6$ mA.cm$^{-2}$
Figure (4.16) Relation between current I and voltage V for sample 10

(Carbon doped with S)

Table(4.11) Relation between current I and voltage for sample 11

(Carbon doped with Cd)

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.66986</td>
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<td>22.72793</td>
<td>0.01363</td>
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<td>22.66986</td>
<td>0.0237</td>
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<td>22.786</td>
<td>0.03117</td>
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<td>23</td>
<td>0.0411</td>
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<tr>
<td>22.85134</td>
<td>0.04732</td>
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<tr>
<td>20.38328</td>
<td>0.05616</td>
</tr>
<tr>
<td>14.56156</td>
<td>0.06324</td>
</tr>
</tbody>
</table>

$I_{sc} = 22.49$ mA
$I_{max} = 19.61$ mA
$V_{max} = 0.0611$ V
$V_{oc} = 0.0655$ V
$FF = 0.81$
$\eta = 0.019\%$
$J_{sc} = 3.6$ mA.cm$^{-2}$
Figure (4.17) Relation between current I and voltage V for Sample 11

(Carbon doped with Cd)

Table (4.12) Relation between current I and voltage for sample 12

(Carbon doped with Cu)

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>Voltage (V)</th>
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<td>0.52534</td>
</tr>
<tr>
<td>51.73803</td>
<td>0.73851</td>
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<tr>
<td>51.49855</td>
<td>0.98711</td>
</tr>
<tr>
<td>50.59869</td>
<td>1.298</td>
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<td>46.03411</td>
<td>1.80058</td>
</tr>
<tr>
<td>37.32583</td>
<td>1.97348</td>
</tr>
<tr>
<td>25.48984</td>
<td>2.04489</td>
</tr>
<tr>
<td>0.08708</td>
<td>2.15212</td>
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</tbody>
</table>
Figure (4.18) Relation between current I and voltage V for Sample 12

(Carbon doped with Cu)

Table (4.13) Performance of all silicon solar cells (from sample 1 to 6)

<table>
<thead>
<tr>
<th>Sample No</th>
<th>Element</th>
<th>Atomic number</th>
<th>$I_{sc}$ (mA)</th>
<th>$I_{max}$ (mA)</th>
<th>$V_{oc}$ (V)</th>
<th>$V_{max}$ (V)</th>
<th>$J_{sc}$ mA/cm$^2$</th>
<th>$\eta$ %</th>
<th>FF</th>
<th>$E_g$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Zn</td>
<td>30</td>
<td>19.32</td>
<td>16.56</td>
<td>0.120</td>
<td>0.105</td>
<td>3.09</td>
<td>0.0280</td>
<td>0.75</td>
<td>5.920</td>
</tr>
<tr>
<td>2</td>
<td>Mg</td>
<td>12</td>
<td>21.17</td>
<td>18.64</td>
<td>0.096</td>
<td>0.082</td>
<td>3.39</td>
<td>0.0250</td>
<td>0.75</td>
<td>6.147</td>
</tr>
</tbody>
</table>
Table (4.14) Performance of all Carbon solar cells (from sample 7 to 12)

<table>
<thead>
<tr>
<th>Sample No</th>
<th>Element</th>
<th>Atomic Number</th>
<th>$I_{sc}$ (mA)</th>
<th>$I_{max}$ (mA)</th>
<th>$V_{oc}$ (V)</th>
<th>$V_{max}$ (V)</th>
<th>$J_{sc}$ mA/cm$^2$</th>
<th>$\eta$ %</th>
<th>FF</th>
<th>$E_g$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Zn</td>
<td>30</td>
<td>37.53</td>
<td>30.27</td>
<td>0.047</td>
<td>0.042</td>
<td>6.00</td>
<td>0.020</td>
<td>0.72</td>
<td>1.925</td>
</tr>
<tr>
<td>8</td>
<td>Mg</td>
<td>12</td>
<td>15.29</td>
<td>12.23</td>
<td>0.056</td>
<td>0.045</td>
<td>2.45</td>
<td>0.009</td>
<td>0.64</td>
<td>1.879</td>
</tr>
<tr>
<td>9</td>
<td>Al</td>
<td>13</td>
<td>78.79</td>
<td>67.00</td>
<td>0.440</td>
<td>0.406</td>
<td>12.60</td>
<td>0.440</td>
<td>0.78</td>
<td>1.897</td>
</tr>
<tr>
<td>10</td>
<td>S</td>
<td>16</td>
<td>16.28</td>
<td>13.67</td>
<td>1.977</td>
<td>1.713</td>
<td>2.60</td>
<td>0.375</td>
<td>0.73</td>
<td>1.918</td>
</tr>
<tr>
<td>11</td>
<td>Cd</td>
<td>48</td>
<td>22.49</td>
<td>19.61</td>
<td>0.065</td>
<td>0.061</td>
<td>3.60</td>
<td>0.019</td>
<td>0.81</td>
<td>1.855</td>
</tr>
<tr>
<td>12</td>
<td>Cu</td>
<td>29</td>
<td>51.48</td>
<td>43.47</td>
<td>2.483</td>
<td>1.877</td>
<td>8.23</td>
<td>1.3</td>
<td>0.64</td>
<td>1.873</td>
</tr>
</tbody>
</table>

4.3 Discussion

Figure (4.1) shows that no absorption takes place for all wavelengths greater than 251 nm for all silicon samples and the absorption is only for short wavelengths. Sample 5 and 6 – which are corresponding to Cd and Cu doping Si respectively, have absorption peaks in the range of 222 – 218 nm. Figure 4.2 shows that, for all the samples with silicon as a host material, increasing photon energy results in increase of absorption coefficient till it takes maximum value. The maximum values of absorption coefficients are greater for samples 5 and 6 - which are corresponding to Cd and Cu doping Si, and lower for samples
2 and 4, which are corresponding to Mg and S doping Si, respectively. Figure (4.4) shows that for all the samples with carbon as a host material, most of the absorption is in the UV-VIS range and the curves have two peaks. The energy gap (Eg) has been calculated using the relation:

$$(\alpha h\nu)^{1/n} = A(h\nu - Eg)$$

where (A) a is constant. The value of n is dependent on the electronic transition type. Where: n=1/2 for direct allowed transition, n = 2 for indirect allowed transition, n = 3 for direct forbidden transition and n=3/2 indirect forbidden transition. By plotting $(\alpha h\nu)^{1/2}$ vs. photon energy $(h\nu)$. In case of direct transition, and by extrapolating the straight portion of the curve to intercept the energy axis, at $(\alpha h\nu)^{1/2} = 0$, the value of the energy gaps can be obtained. In the tables (4.13) and (4.14), the open circuit voltage $V_{oc}$ is obtained from the I-V curves when $I = 0$ and the short circuit $I_{sc}$ is obtained from the same curves when $V = 0$. The solar cell parameter Fill Factor is obtained from the relation: $FF = \frac{I_{max}V_{max}}{I_{sc}V_{oc}}$, where $I_{max}$ and $V_{max}$ is the maximum current and voltage corresponding to the maximum power point. The efficiency is given by

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{mp}I_{mp}}{P_{in}} = \frac{V_{oc}I_{sc}FF}{P_{in}}$$

In this work the silicon and carbon acts as host substrate for the samples which are doped with Mg, Al, S, Cu, Zn and Cd. When silicon is doped with Al, S, and Cu having atomic numbers 13, 16, and 29, the efficiency values were found to be 0.0650, 0.0560, and 0.0090, respectively. The efficiency decrease due to increase of atomic number, may be related to the fact that increasing the atomic number, increases nuclear attraction of electron. This decreases electron velocity and the probability of escape which is related to the concentration of free carriers. This result agrees with the study of Ali which found that the change of anode atomic number changes the efficiency, where the increase of atomic number to be 13 (Al), 47 (Gl), and 79 (Au) decreases the efficiency to be 1.66, 1.59 and 1.58, respectively. (Ali et al., 2016).

For silicon doped with Cu, Zn and Cd with atomic numbers 29, 30 and 48 the efficiency increases as the atomic number increases. This may be explained by assuming that atoms act as electronic dipoles with internal field in the direction of the externally applied magnetic field. In this case the increase of atomic number increases the internal field, which increases the electrons velocity. This increase the current which in turn increases
the efficiency. This relation between current increase and efficiency increase agrees with Mokhtar study which shows that increase of Zn concentration increases carrier and current concentration thus increases the efficiency (Mokhtar et al., 2017).

Another explanation is related to the effect of nuclear magnetic dipole moment on the energy gap. By assuming that all the nucleons align themselves in the same direction. This means that increasing atomic number increases the magnetic nuclear dipole field, which in turn increases the energy spacing between splitted energy sublevels. This of course gives a chance to a large number of sublevels near conduction and valence bands edges to enter the energy gap. Thus, increasing atomic number increases the number of sublevels that enter the forbidden band. This causes the energy gap to be narrower which in turn increases the efficiency. This interpretation of the result obtained agrees with the work of Mohamed who shows that changing the dye which dopes the polymer causes the energy gap to change. (Mohamed et al., 2016)

The effect of changing the mass density of the impurities changes the energy gap, where the increase of mass density, which is related to compound atomic number, causes the energy gap to decrease. (Elmahdi et al., 2017).

When the host material is changed from silicon to carbon, the general features of the efficiency of the resulting solar cells can be explained by the same mechanism where the efficiency decreases with atomic number for Al, S, Zn and Cd. which have atomic numbers 13,16 ,30 and 48 . The efficiency decreases and take the values 0.440, 0.375, 0.020 and 0.019 . For Mg, Al and Cu which have atomic numbers 12,13 and 29 ,respectively, the efficiency increases with atomic numbers and take the values 0.009, 0.440 and 1.3, respectively. The change of efficiency due to the change of atomic or dopant materials type agrees with the work done by Gasim (Gasim et al., 2014) and Ali (Ali et al., 2017) which are concerned with changing of the efficiency due to the change dye type.

Chapter Five
Conclusions and Recommendations
5.1 Conclusions

The experiment on silicon and carbon doped by metals shows that the efficiency and performance of the solar cell are affected by the host material as well as by the impurities. The efficiency of silicon is higher than that of carbon as host material. The atomic number of the impurities seem to affect the performance in general. These includes efficiency, fill factor, open besides maximum voltage and short beside maximum current. The absorption patterns are affected as well by the host material and impurities. The energy gap is also affected by the host material and impurities.

5.2 Recommendations

To understand the behavior of solar cells and the factors that affect their performance it is important to widen the scope of this study to be stretched in different directions. First of all the host material must be changed to include other organic as well as inorganic semiconductors. The impurities should also be changed by selecting cheap and commercially available materials. Other factors like valence and electron affinity beside ionization energy and work function should also be included. Thermal effects need to be also taken into account.
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