

# **The Study of Materials Properties For Quantum Dot Solar Cell**



# EAST WEST UNIVERSITY

Project title

**The study of Materials Properties for Quantum Dot Solar Cell**

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## Declaration

This report on the basis of our thesis paper and its enhancement of studies throughout our thesis work is submitted to follow the terms and condition of the department of electronics and communications engineering .This report is the requirement for the successive competition of B.Sc engineering in Electronics and communication engineering.

We state that the report along with its literature that has been demonstrated in this report papers, is our own work with the masterly guidance and fruitful assistance of our supervisor for the finalization of our report successfully.

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## **Approval**

This project report “quantum dot solar cells” submitted by Shamanta Shome Puja , ID: 2012-2-55-027 and Jedni Jerin , ID: 2012-1-55-016 to department of Electronics and Communication Engineering. East West University has been accepted as satisfactory for the partial fulfillment of the requirements for the degree of Bachelor of Science in Electronics and Communication Engineering and approved as to its style and contents.

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## Abstract

A **quantum dot solar cell** is a solar cell design that uses quantum dots as the absorbing photovoltaic material. Quantum dot (QD) solar cells have the potential to increase the maximum attainable thermodynamic conversion efficiency of solar photon conversion up to about 66% by utilizing hot photo generated carriers to produce higher photo voltages or higher photocurrents. The main advantage with quantum dots is the ability to tune the size of the dots for many applications. Their electronic characteristics are closely related to the size and shape of the individual crystals. In this work we have studied the Quantum dot solar cell properties of 5 different semiconductor materials such as( InAs, InSb, PbS, PbSe, PbTe) and which can captured all solar radiation spectrum. It is found that **InSb** semiconductor material QDs have the smallest size for Quantum dot solar cell spectrum.

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# Chapter 1

## 1.1 Introduction:

A solar cell photovoltaic cell, is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect, which is a physical and chemical phenomenon [1]. It is a form of photoelectric cell, defined as a device whose electrical characteristics, such as current, voltage, or resistance, vary when exposed to light. Solar cells are the building blocks of photovoltaic modules, otherwise known as solar panels.

Solar cells are described as being photovoltaic irrespective of whether the source is sunlight or an artificial light. They are used as a photo detector (for example infrared detectors), detecting light or other electromagnetic radiation near the visible range, or measuring light intensity.

## 1.2 Emerging photovoltaic cell:

A solar cell (also called a photovoltaic cell) is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect. It is a form of photoelectric cell (in that its electrical characteristics—e.g. current, voltage, or resistance—vary when light is incident upon it) which, when exposed to light, can generate and support an electric current without being attached to any external voltage source. 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. An organic solar cell or plastic solar cell is a type of polymer solar cell that uses organic electronics, a branch of electronics that deals with conductive organic polymers or small organic molecules, for light absorption and charge transport to produce electricity from sunlight by the photovoltaic effect. Quantum dot solar cells are an emerging field in solar cell research that uses quantum dots as the absorbing photovoltaic material, as opposed to better-known bulk materials such as silicon, copper indium gallium selenide . QD solar cells have been realized as photo electrochemical cells and solid-state devices. Multi - junction solar cells or tandem cells are solar cells containing several p-n junctions. Each

junction is tuned to a different wavelength of light, reducing one of the largest inherent sources of losses, and thereby increasing efficiency.

### 1.3 History of Emerging Solar cell:

An American inventor, Charles Fritts, was the first that came up with plans for how to make solar cells. His simple designs in the late 19<sup>th</sup> century were based on selenium wafers.

David Chapin, Calvin Fuller and Gerald Pearson of Bell Labs are credited with the world's first photovoltaic cell (solar cell). In other words, these are the men that made the first device that converted sunlight into electrical power. They later pushed the conversion efficiency from 4% to 11%.

The photovoltaic effect was first experimentally demonstrated by French physicist A. E. Becquerel. In 1839, at age 19, experimenting in his father's laboratory, he built the world's first photovoltaic cell. Willoughby Smith first described the "Effect of Light on Selenium during the passage of an Electric Current" in an article that was published in the 20 February 1873 issue of Nature.

### 1.4 Sunlight:

**Sunlight is the result of electromagnetic radiation being emitted from the sun.** Ultraviolet, visible and infrared light are the result of this radiation, and they have a profound effect on the Earth.

Visible sunlight is typically called daylight. It is filtered through the Earth's atmosphere and gives off radiant heat. The effects of sunlight are varied, causing positive and negative effects on the human body.

## 1.5 Sun is power source of earth:

**The sun benefits the Earth in several ways, including giving the light animals see with or the energy needed to produce artificial light, the heat that makes life on Earth possible, and energy for plants to make food through photosynthesis of sunlight.** Plants are the basis of any food chain. Life as humans understand it isn't possible on Earth without the sun because water would be frozen. Because the Earth is just the right distance from the sun, its water is liquid. On the inner planets Mercury and Venus, any water exists in the form of steam; on Mars and planets beyond it, any water takes the form of ice.

Plants, which are called "producers" because they make their food from just sunlight and inorganic minerals, are necessary to support life. Organisms that eat other organisms, or "consumers," eat either plants or other organisms that eat plants. Energy from the sun is stored in various ways on Earth, not just in food. Sunlight is necessary to produce hydrocarbons such as coal, which is fossilized plant matter, and petroleum, which is fossilized zooplankton and algae. Modern society would not function well without hydrocarbons. Even ancient people used the fossil fuels, animal fats, manure and wood made possible by sunlight to cook food and heat their homes.



Fig 1.1: A day sunlight

## 1.6 Construction and Working principle of solar cell:

Various materials display varying efficiencies and have varying costs. Materials for efficient solar cells must have characteristics matched to the spectrum of available light. Some cells are designed to efficiently convert wavelengths of solar light that reach the Earth surface. However, some solar cells are optimized for light absorption beyond earth's atmosphere as well. Light absorbing materials can often be used in multiple physical configurations to take advantage of different light absorption and charge separation mechanisms. Many currently available solar cells are made from bulk materials that are cut into wafers between 180 to 240 micrometers thick that are then processed like other semiconductors. Other materials are made as thin-films layers, organic dyes, and organic polymers that are deposited on supporting substrates. A third group are made from nanocrystals and used as quantum dots (electron confined nanoparticles). Silicon remains the only material that is well-researched in both bulk and thin-film forms.

The solar cell works in three steps:

- 1) Photons in sunlight hit the solar panel and are absorbed by semiconducting materials, such as silicon.
- 2) Electrons (negatively charged) are knocked loose from their atoms, causing an electric potential difference. Current starts flowing through the material to cancel the potential and this electricity is captured. Due to the special composition of solar cells, the electrons are only allowed to move in a single direction.
- 3) An array of solar cells converts solar energy into amusable amount of direct current (DC) electricity.

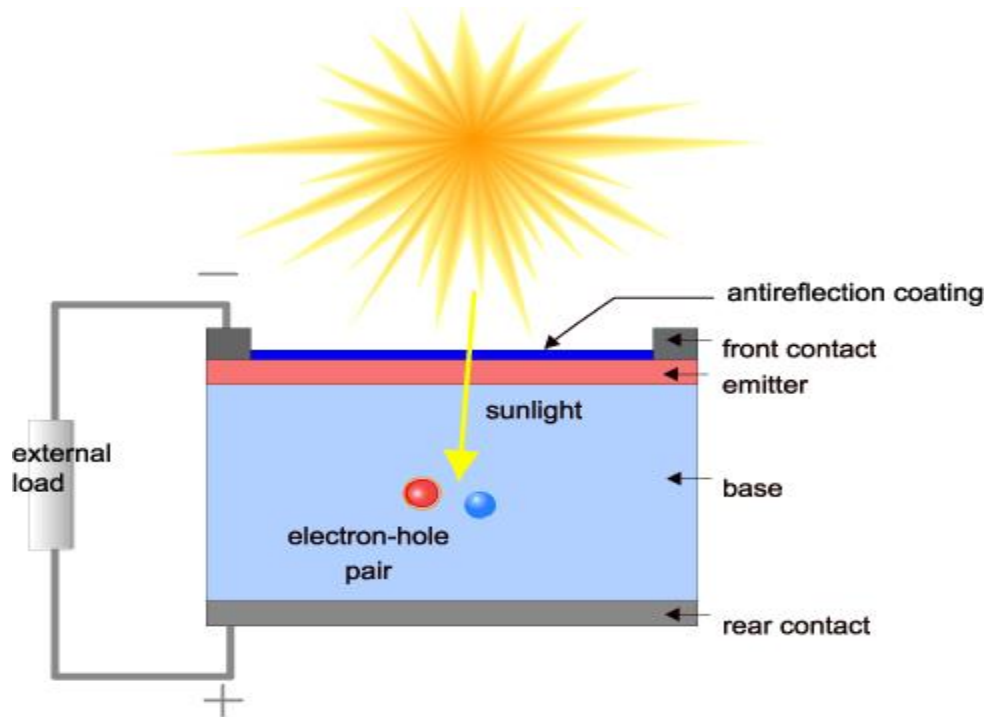


Fig 1.2: Structure of Solar cell

### 1.8 Demand of solar cell:

Renewable energy is generally defined as energy that is collected from resources which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat [2]. Renewable energy often provides energy in four important areas: electricity generation, air and water heating/cooling, transportation, and rural (off-grid) energy services [3].

Based on REN21's 2014 report, renewable contributed 19 percent to humans' global energy consumption and 22 percent to their generation of electricity in 2012 and 2013, respectively. This energy consumption is divided as 9% coming from traditional biomass, 4.2% as heat energy (non-biomass), 3.8% hydro electricity and 2% is electricity from wind, solar, geothermal, and biomass. Worldwide investments in renewable technologies amounted to more than US\$214 billion in 2013, with countries like China and the United States heavily investing in wind, hydro, solar and biofuels [4].

Renewable energy resources exist over wide geographical areas, in contrast to other energy sources, which are concentrated in a limited number of countries. Rapid deployment of renewable energy and energy efficiency is resulting in significant energy

security, climate change mitigation, and economic benefits [5]. In international public opinion surveys there is strong support for promoting renewable sources such as solar power and wind power [6]. At the national level, at least 30 nations around the world already have renewable energy contributing more than 20 percent of energy supply. National renewable energy markets are projected to continue to grow strongly in the coming decade and beyond [7]. Some places and at least two countries, Iceland and Norway generate all their electricity using renewable energy already, and many other countries have the set a goal to reach 100% renewable energy in the future. For example, in Denmark the government decided to switch the total energy supply (electricity, mobility and heating/cooling) to 100% renewable energy by 2050 [8]. While many renewable energy projects are large-scale, renewable technologies are also suited to rural and remote areas and developing countries, where energy is often crucial in human development[9]. United Nations' Secretary-General Ban Ki-moon has said that renewable energy has the ability to lift the poorest nations to new levels of prosperity [9]. As most of renewable provide electricity, renewable energy deployment is often applied in conjunction with further electrification, which has several benefits: For example, electricity can be converted to heat without losses and even reach higher temperatures than fossil fuels, can be converted into mechanical energy with high efficiency and is clean at the point of consumption [10][11]. In addition to that electrification with renewable energy is much more efficient and therefore leads to a significant reduction in primary energy requirements, because most renewable don't have a steam cycle with high losses (fossil power plants usually have losses of 40 to 65%) [12].

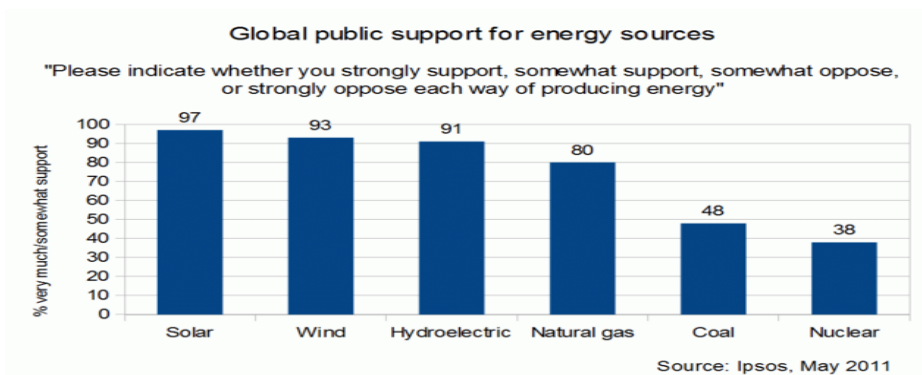


Fig 1.3: The potential for renewable energy source.

## Chapter 2

### Types of solar cell

#### 2.1 Introduction:

Solar cells are typically named after the semiconducting material they are made of. These materials must have certain characteristics in order to absorb sunlight. Some cells are designed to handle sunlight that reaches the Earth's surface, while others are optimized for use in space. Solar cells can be made of only one single layer of light-absorbing material (single-junction) or use multiple physical configurations (multi-junctions) to take advantage of various absorption and charge separation mechanisms.

#### 2.2 Photovoltaic generation:

Solar cell divided into three main categories called generation

##### 2.2.1 1st generation solar cell:

The first generation cells—also called conventional, traditional or wafer-based cells—are made of crystalline silicon, the commercially predominant PV technology that includes materials such as poly silicon and mono crystalline silicon.

“First generation” panels include silicon solar cells. They are made from a single silicon crystal (mono-crystalline), or cut from a block of silicon that is made up of many crystals (multi-crystalline - shown at right).

##### 2.2.2 2<sup>nd</sup> generation solar cell:

Second generation cells are thin film solar cells, that include amorphous silicon, CdTe and CIGS cells and are

Commercially significant in utility-scale photovoltaic power stations, building integrated photo voltaic or in small standalone power system.

“Second generation” thin-film solar cells are less expensive to produce than traditional silicon solar cells as



They require a decreased amount of materials for construction. The thin-film PV cells are, just as the name implies, a physically thin technology that has been applied to photovoltaic's. They are only slightly less efficient than other types but do require more surface area to generate the same amount of power.

### 2.2.3 3<sup>rd</sup> generation solar cell:

The third generation of solar cells includes a number of thin-film technologies often described as emerging photo voltaic most of them have not yet been commercially applied and are still in the research or development phase.

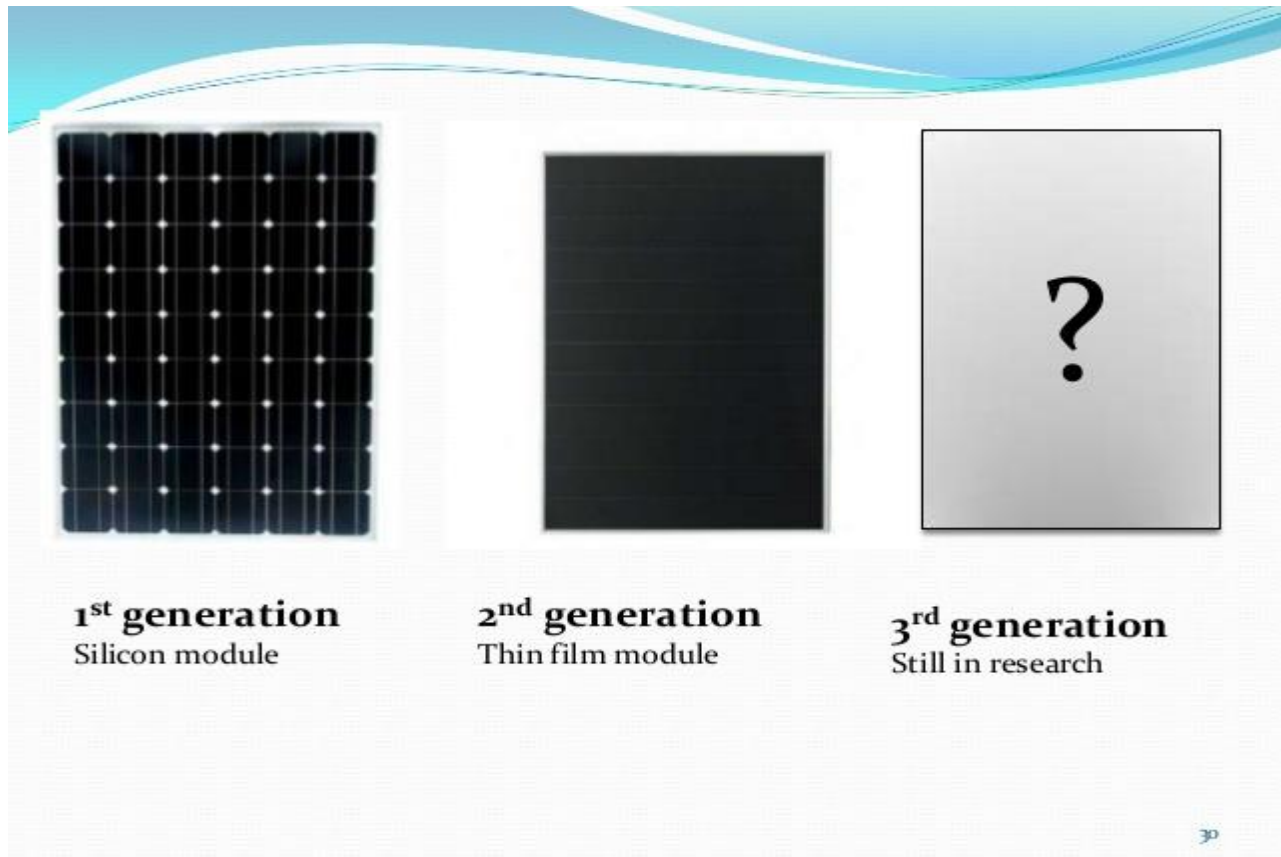


Fig 2.1: Generation of solar cell

## 2.3 Type of solar cell:

A solar cell (also called photovoltaic cell or photoelectric cell) is a solid state electrical device that converts the energy of light directly into electricity by the photovoltaic effect. The following are the different types of solar cells.

- \*Amorphous Silicon solar cell (a-Si)
- \*Cadmium telluride solar cell (CdTe)
- \*Concentrated PV cell (CVP and HCVP)
- \*Crystalline silicon solar cell (c-Si)
- \*Gallium arsenide germanium solar cell (GaAs)
- \*Hybrid solar cell
- \*Multi-junction solar cell (MJ)
- \*Organic solar cell (OPV)
- \*Plastic solar cell
- \*Polycrystalline solar cell (multi-Si)
- \*Polymer solar cell
- \*Quantum dot solar cell
- \*Solid-state solar cell
- \*Wafer solar cell, or wafer-based solar cell (synonym for crystalline silicon solar cell)

In this chapter we discussed about some of these types of solar cell.

### 2.3.1 Amorphous Silicon solar cell (a-Si) :

**Amorphous silicon (a-Si)** is the non-crystalline form of silicon used for solar cells and thin-film transistors in LCD displays.

Used as semiconductor material for **a-Si solar cells**, or **thin-film silicon solar cells**, it is deposited in thin films onto a variety of flexible substrates, such as glass, metal and plastic. Amorphous silicon cells generally feature low efficiency, but are one of the most environmentally friendly photovoltaic technologies, since they do not use any toxic heavy metals such as cadmium or lead.

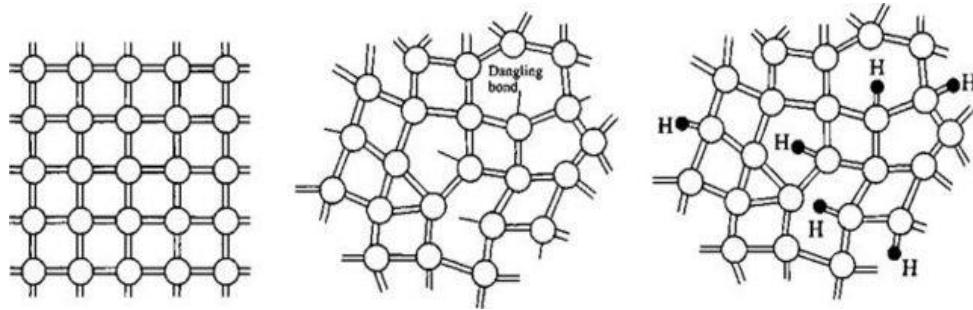


Fig 2.2: Amorphous Silicon solar cell (a-Si)

As a second-generation thin-film solar cell technology, amorphous silicon was once expected to become a major contributor in the fast-growing worldwide photovoltaic market, but has since lost its significance due to strong competition from conventional crystalline silicon cells and other thin-film technologies such as CdTe and CIGS.

Amorphous silicon differs from other allotropic variations, such as mono crystalline silicon—a single crystal, and poly crystalline silicon, that consists of small grains, also known as crystallites.

### 2.3.2 Cadmium telluride solar cell (CdTe):

**Cadmium telluride (CdTe) photovoltaic's** describes a photovoltaic (PV) technology that is based on the use of cadmium telluride, a thin semiconductor layer designed to absorb and convert sunlight into electricity [13]. Cadmium telluride PV is the only thin film technology with lower costs than conventional solar cells made of crystalline silicon in multi-kilowatt systems[14] [15] [16]. On a lifecycle basis, CdTe PV has the smallest

carbon footprint, lowest water use and shortest energy payback time of all solar technologies. CdTe's energy payback time of less than a year allows for faster carbon reductions without short-term energy deficits.



Fig 2.3: Cadmium telluride solar cell (CdTe)

### 2.3.3 Concentrated PV cell (CVP and HCVP):

**Concentrator photovoltaics (CPV)** is a photovoltaic technology that generates electricity from sunlight. Contrary to conventional photovoltaic systems, 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. Ongoing research and development is rapidly improving their competitiveness in the utility-scale segment and in areas of high solar isolation. This sort of solar technology can be thus used in smaller areas.



Fig 2.4: Concentrated PV cell (CVP and HCVP)

## 2.3.4 Solar cell characteristic

### 2.3.4.1 Introduction:

Solar energy in one form or another is the source of nearly all energy on the earth. Humans, like all other animals and plants, rely on the sun for warmth and food. However, people also harness the sun's energy in many other different ways. For example, fossil fuels, plant matter from a past geological age, is used for transportation and electricity generation and is essentially just stored solar energy from millions of years ago. Similarly, biomass converts the sun's energy into a fuel, which can then be used for heat, transport or electricity. Wind energy, used for hundred of years to provide mechanical energy or for transportation, uses air currents that are created by solar heated air and the rotation of the earth. Photovoltaic's (often abbreviated as PV) is a simple and elegant method of harnessing the sun's energy. PV devices (solar cells) are unique in that they directly convert the incident solar radiation into electricity, with no noise, pollution or moving parts, making them robust, reliable and long lasting.

### 2.3.4.2 Parameters of solar cell:

Several important parameters which are used to characterise solar cells

1. Short circuit current
2. Open circuit voltage
3. Fill factor
4. Efficiency

#### 1. Short circuit current:

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). Usually written as  $I_{sc}$ , the short-circuit current is shown on the IV curve below.

The short-circuit current is due to the generation and collection of light-generated carriers. For an ideal solar cell at most moderate resistive loss mechanisms, the short-circuit current and the light-generated current are identical. Therefore, the short-circuit current is the largest current which may be drawn from the solar cell.

The short-circuit current depends on a number of factors which are described below:

- **the area of the solar cell.** To remove the dependence of the solar cell area, it is more common to list the short-circuit current **density** ( $J_{sc}$  in mA/cm<sup>2</sup>) rather than the short-circuit current;
- **the number of photons** (i.e., the power of the incident light source).  $I_{sc}$  from a solar cell is directly dependant on the light intensity as discussed in Effect of Light Intensity;
- **the spectrum of the incident light.** For most solar cell measurement, the spectrum is standardised to the AM1.5 spectrum;
- **the optical properties** (absorption and reflection) of the solar cell (discussed in Optical Losses); and
- **the collection probability** of the solar cell, which depends chiefly on the surface passivation and the minority carrier lifetime in the base

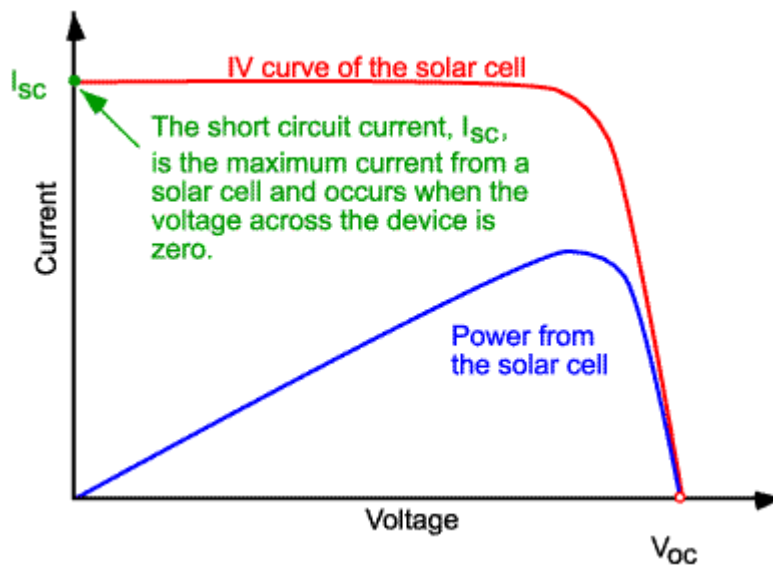


Fig 2.5: IV curve of a solar cell showing the short-circuit current

When comparing solar cells of the same material type, the most critical material parameter is the diffusion length and surface passivation. In a cell with perfectly passivated surface and uniform generation, the equation for the short-circuit current can be approximated as:

$$J_{SC} = qG(L_n + L_p) \dots\dots\dots (2.1)$$

where G is the generation rate, and  $L_n$  and  $L_p$  are the electron and hole diffusion lengths respectively.

Silicon solar cells under an AM1.5 spectrum have a maximum possible current of 46 mA/cm<sup>2</sup>. Laboratory devices have measured short-circuit currents of over 42 mA/cm<sup>2</sup>, and commercial solar cell have short-circuit currents between about 28 mA/cm<sup>2</sup> and 35 mA/cm<sup>2</sup>.

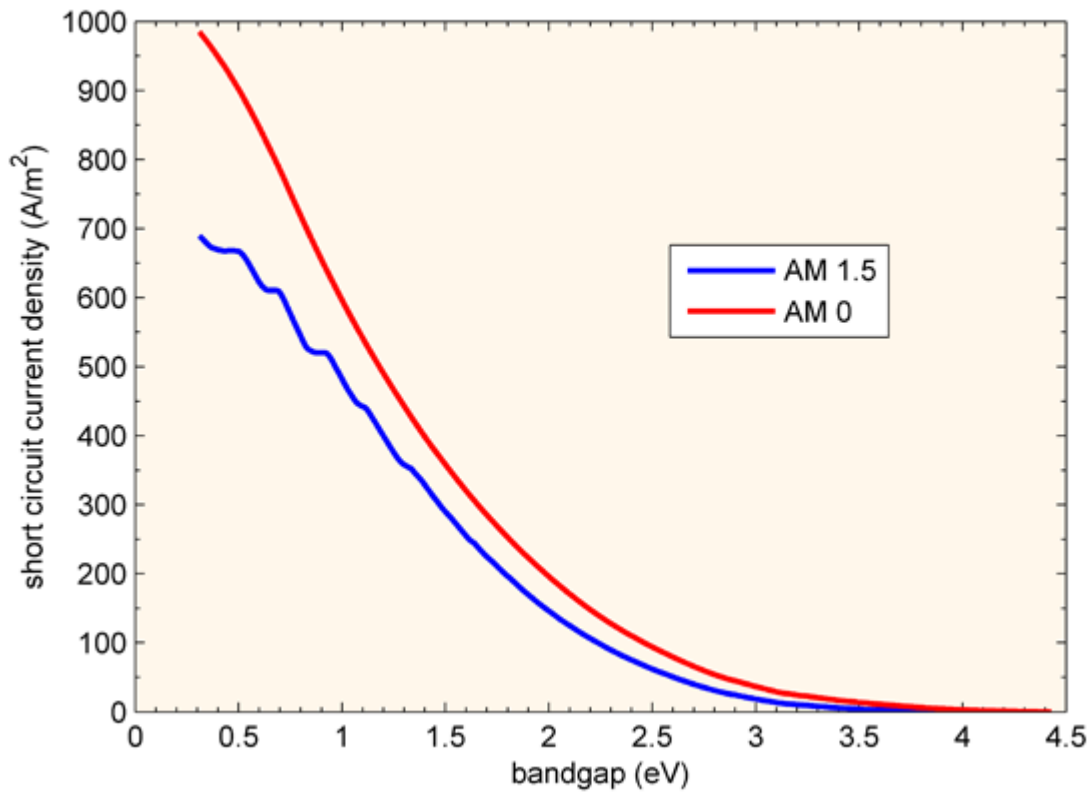


Fig 2.6: In an ideal device every photon above the band gap gives one charge carrier in the external circuit so the highest current is for the lowest band gap.

## 2. Open Circuit Voltage:

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

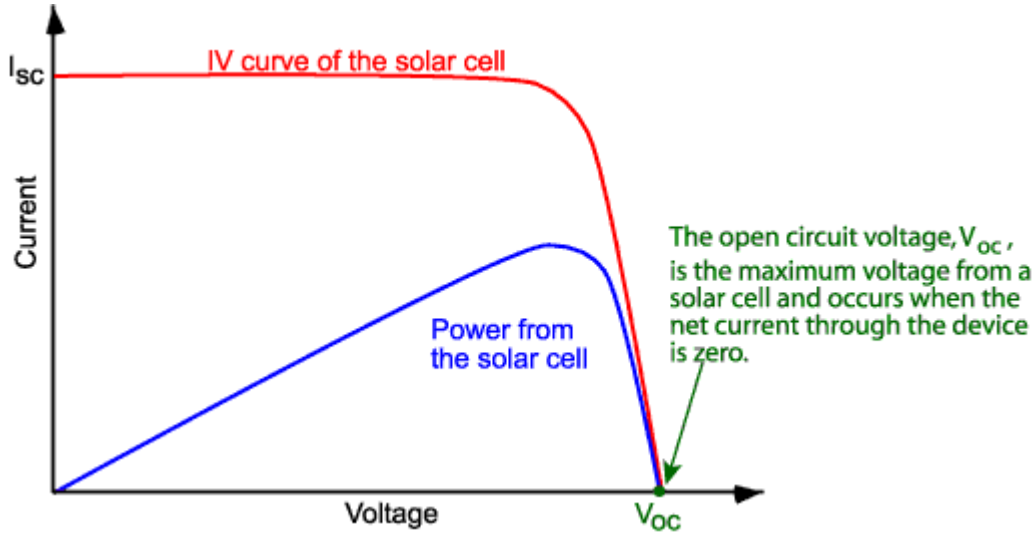


Fig 2.7: IV curve of a solar cell showing the open-circuit voltage.

An equation for  $V_{oc}$  is found by setting the net current equal to zero in the solar cell equation to give:

$$V_{OC} = \frac{nkT}{q} \ln \left( \frac{I_L}{I_0} + 1 \right) \dots\dots\dots (2.2)$$

The  $V_{OC}$  can also be determined from the carrier concentration

$$V_{OC} = \frac{kT}{q} \ln \left[ \frac{(N_A + \Delta n)\Delta n}{n_i^2} \right] \dots\dots\dots (2.3)$$

where  $kT/q$  is the thermal voltage,  $N_A$  is the doping concentration,  $\Delta n$  is the excess carrier concentration and  $n_i$  is the intrinsic carrier concentration. The determination of  $V_{OC}$  from the carrier concentration is also termed Implied  $V_{OC}$ .



Where the short-circuit current ( $I_{SC}$ ) decreases with increasing bandgap, the open-circuit voltage increases as the band gap increases. In an ideal device the  $V_{OC}$  is limited by radiative recombination and the analysis uses the principle of detailed balance to determine the minimum possible value for  $J_0$ .

The minimum value of the diode saturation current is given by:

$$J_0 = \frac{q}{k} \frac{15\sigma}{\pi^4} T^3 \int_u^\infty \frac{x^2}{e^x - 1} dx,$$

where  $q$  is the electronic charge,  $\sigma$  is the Stefan–Boltzmann constant,  $k$  is Boltzmann constant,  $T$  is the temperature and

$$u = \frac{E_G}{kT}$$

Evaluating the integral in the above equation is quite complex. The graph below uses the method

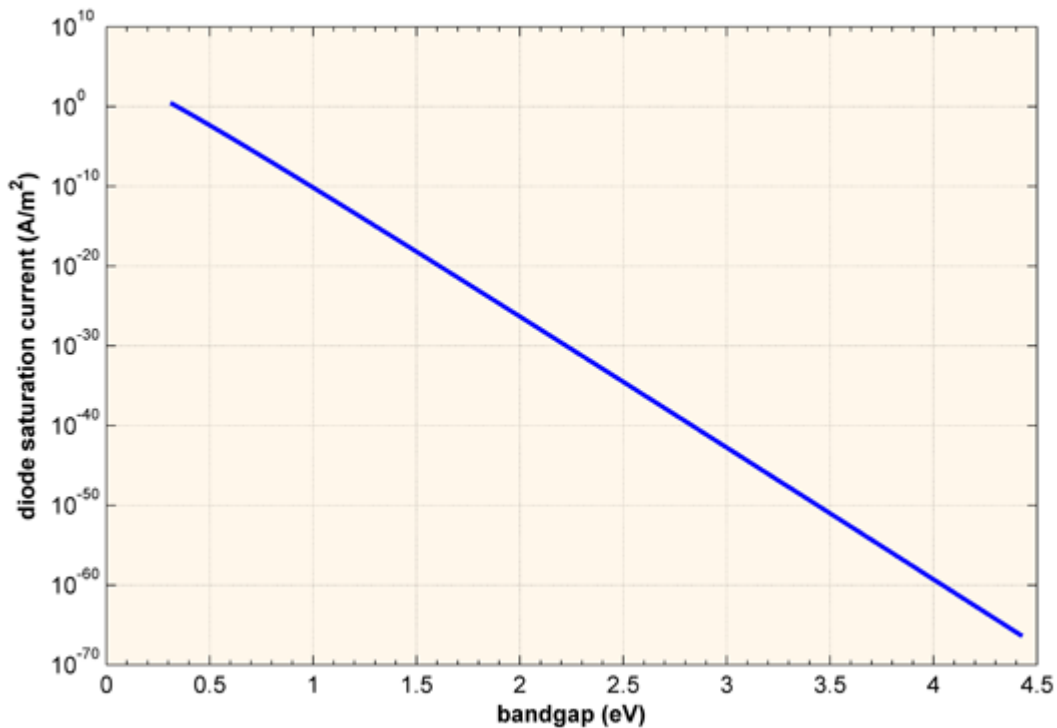


Fig 2.8: Diode saturation current as a function of band gap. The values are determined from detailed balance and place a limit on the open circuit voltage of a solar cell.

The  $J_0$  calculated above can be directly plugged into the standard solar cell equation given at the top of the page to determine the  $V_{OC}$  so long as the voltage is less than the band gap, as is the case under one sun illumination.

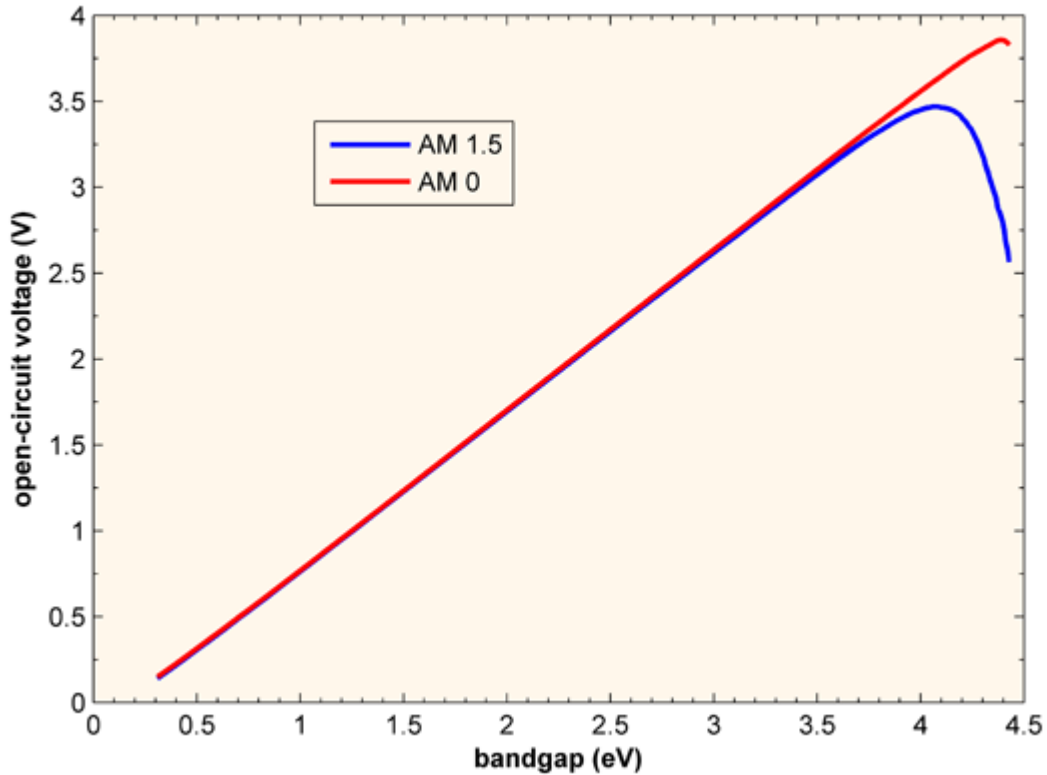


Fig 2.9:  $V_{OC}$  as function of band gap for a cell with AM 0 and AM 1.5. The  $V_{OC}$  increases with band gap as the recombination current falls. There is drop off in  $V_{OC}$  at very high band gaps due to the very low  $I_{SC}$ .

### 3. Fill Factor:

Another defining term in the overall behavior of a solar cell is the fill factor (FF). This is the available power at the maximum power point ( $P_m$ ) divided by the open circuit voltage ( $V_{OC}$ ) and the short circuit current ( $I_{SC}$ ):

$$FF = \frac{V_{MP} I_{MP}}{V_{OC} I_{SC}} \dots\dots\dots (2.4)$$

The fill factor is directly affected by the values of the cell's series, shunt resistances and diodes losses. Increasing the shunt resistance ( $R_{sh}$ ) and decreasing the series resistance ( $R_s$ ) lead to a higher fill factor, thus resulting in greater efficiency, and bringing the cell's output power closer to its theoretical maximum.<sup>[12]</sup>

The Fill factor has a value around 80% for a normal silicon PV cell.

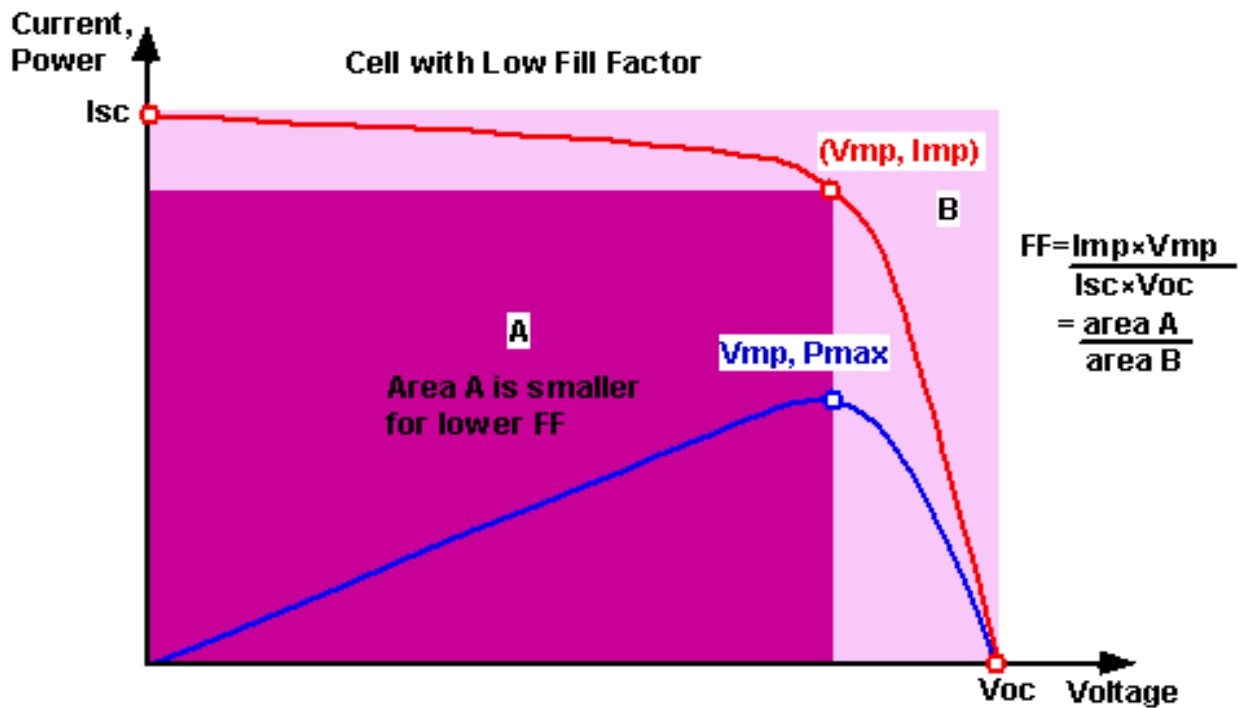


Fig 2.10: Graph of cell output current (red line) and power (blue line) as function of voltage

#### 4. Efficiency:

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell. Therefore, conditions under which efficiency is measured must be carefully controlled in order to compare the performance of one device to another. Terrestrial solar cells are measured under AM1.5 conditions and at a temperature of 25°C. Solar cells intended for space use are measured under AM0 conditions.

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

$$P_{max} = V_{OC}I_{SC}FF$$
$$\eta = \frac{V_{OC}I_{SC}FF}{P_{in}} \dots\dots\dots (2.5)$$

Where Voc is the open circuit voltage

Isc is the short circuit current

FF is the fill factor

η is the Efficiency

The input power for efficiency calculations is 1 kW/m<sup>2</sup> or 100 mW/cm<sup>2</sup>. Thus the input power for a 100 × 100 mm<sup>2</sup> cell is 10 W and for a 156 × 156 mm<sup>2</sup> cell is 24.3 W

## Solar cell efficiency record

Classification	Efficiency	Device Description	Area (cm <sup>2</sup> )	V <sub>oc</sub> (V)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)
Cell (concentrator)	41.1 %	Ga <sub>0.35</sub> In <sub>0.65</sub> P/Ga <sub>0.83</sub> In <sub>0.17</sub> As/Ge triple-junction, 454x, AM1.5d. (Fraunhofer-ISE <a href="#">[1]</a> )	0.0509	2.867	Isc = 380.5 mA	87.2
Cell at one-sun	35.8 %	InGaP/GaAs/InGaAs (Sharp <a href="#">[2]</a> )	3.989 (t)	2.622	14.37	85
Silicon cell (one-sun)	25 %	UNSW PERL <a href="#">[3]</a>	4.00 (da)	0.706	42.7	82.8
Module (concentrator)	27 %	Entech <a href="#">[4]</a>	34 (ap)			
Module (one-sun)	22.7 %	UNSW PERL <a href="#">[5]</a>	778 (da)	5.6	3.93*	80.3
Module (production)	20.4 %**	Sunpower <a href="#">[6]</a>	16300 (t)	68.6	6.12*	79.1

\* Isc (A) for module

\*\* Best cell efficiency 24.2%

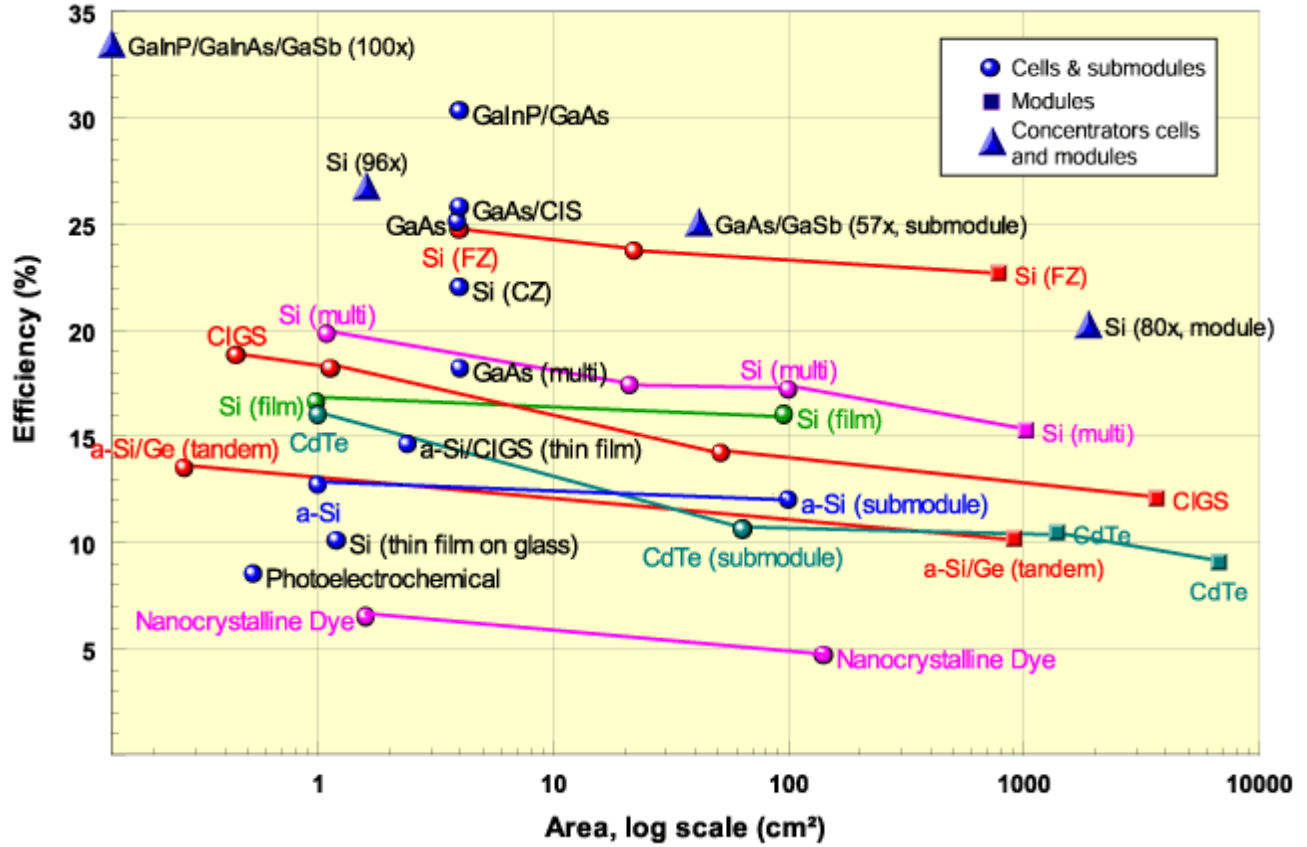


Fig 2.11: Solar cell efficiency records as a function of cell area. Larger cells and modules tend to have a lower efficiency.

## Chapter 3

# Quantum Dot Based Solar cell and Types

### 3.1 Introduction:

One of the foremost challenges in solar cells industry is reducing the cost/watt of delivered solar electricity. In conventional microstructures (bulk) single junction solar cells, photons with energies less than semiconductor band gap are not harvested while those with energies much larger than the band gap produce hot-carriers and upon cooling down (thermalization) the excess energy get wasted as heat. Therefore, novel materials or structures with tunable band gap or intermediate band that can be tuned to match the spectral distribution of solar spectrum are crucial. Quantum dots (QDs) have the advantage of tunable band gap as a result of size variation as well as formation of intermediate bands. In contrast to traditional semiconductor materials that are crystalline or amorphous, quantum dots can be molded into a variety of different types, in two-dimensional (sheets) or three-dimensional arrays. They can be processed to create junctions on inexpensive substrates such as plastics, glass or metal sheets. They can easily be combined with organic polymers and dyes.

### 3.2 Quantum Dot

Quantum dots are a special class of semiconductors, which are nanocrystals, composed of periodic groups of II-VI, III-V, or IV-VI materials and can confine electrons (quantum confinement). When the size of a QD approaches the size of the material's exciton Bohr radius, quantum confinement effect becomes prominent and electron energy levels can no longer be treated as continuous band, they must be treated as discrete energy levels. Hence, QD can be considered as an artificial molecule with energy gap and energy levels spacing dependent on its size (radius). The energy band gap increases with a decrease in size of the quantum dot, as shown in Figure 4. As the size of a QD increases its absorption peak is red shifted due to shrinkage of its band gap (see Figure 5). The adjustable band gap of quantum dots allow the construction of nanostructure solar cell that is able to harvest more of the solar spectrum. QDs have large intrinsic dipole moments, which may lead to rapid charge separation.

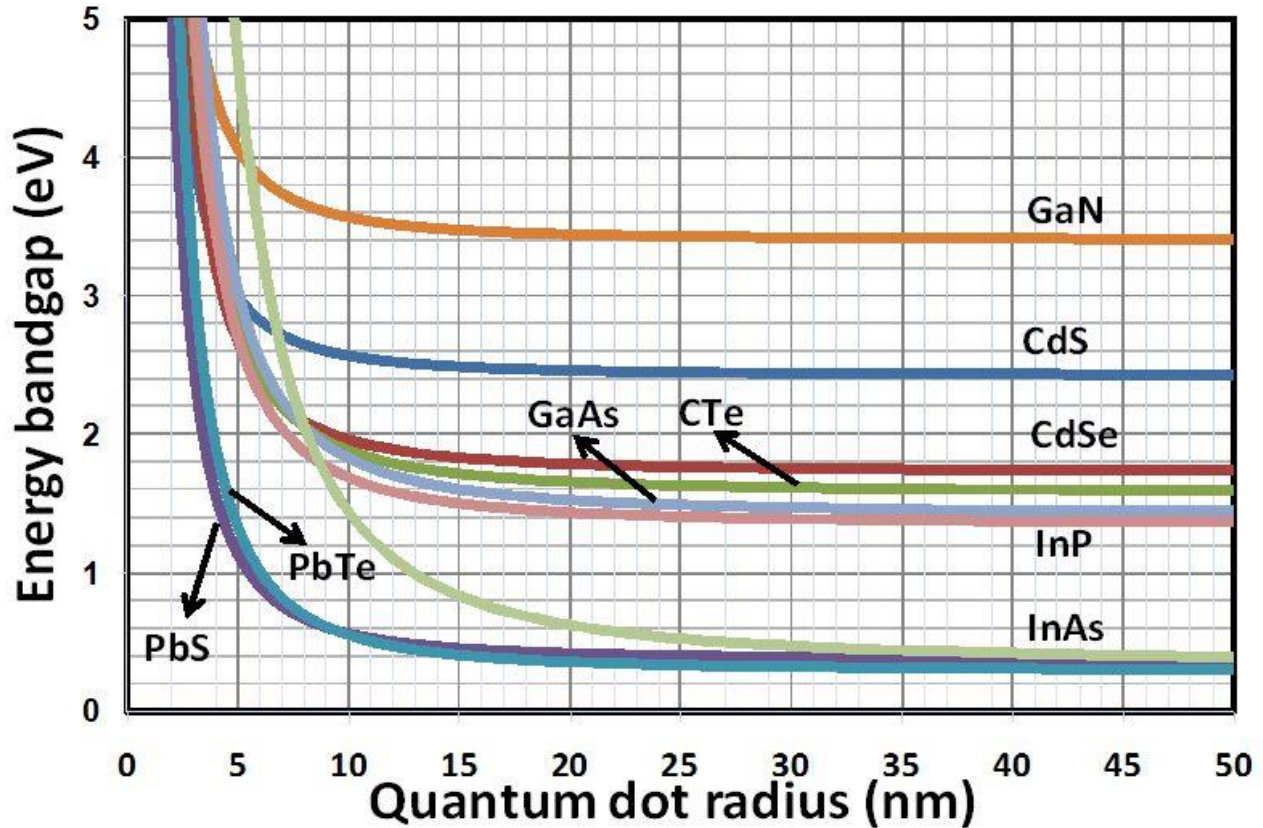


Fig 3.1: Variation of Quantum dot energy band gap vs. dot size for some common semiconductor

Figure 3.1 presents few examples of well-known quantum dots, only the first and the second terms have been considered. Other detailed models such as the strong confinement model [17] have been adopted in determining the quantum dot sizes such as CdS.

Figure 3.2 shows the measured absorbance of three different sizes of lead sulfide (PbS) quantum dots suspended in toluene using dual beam spectrophotometer. Since a quantum dot band gap 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.



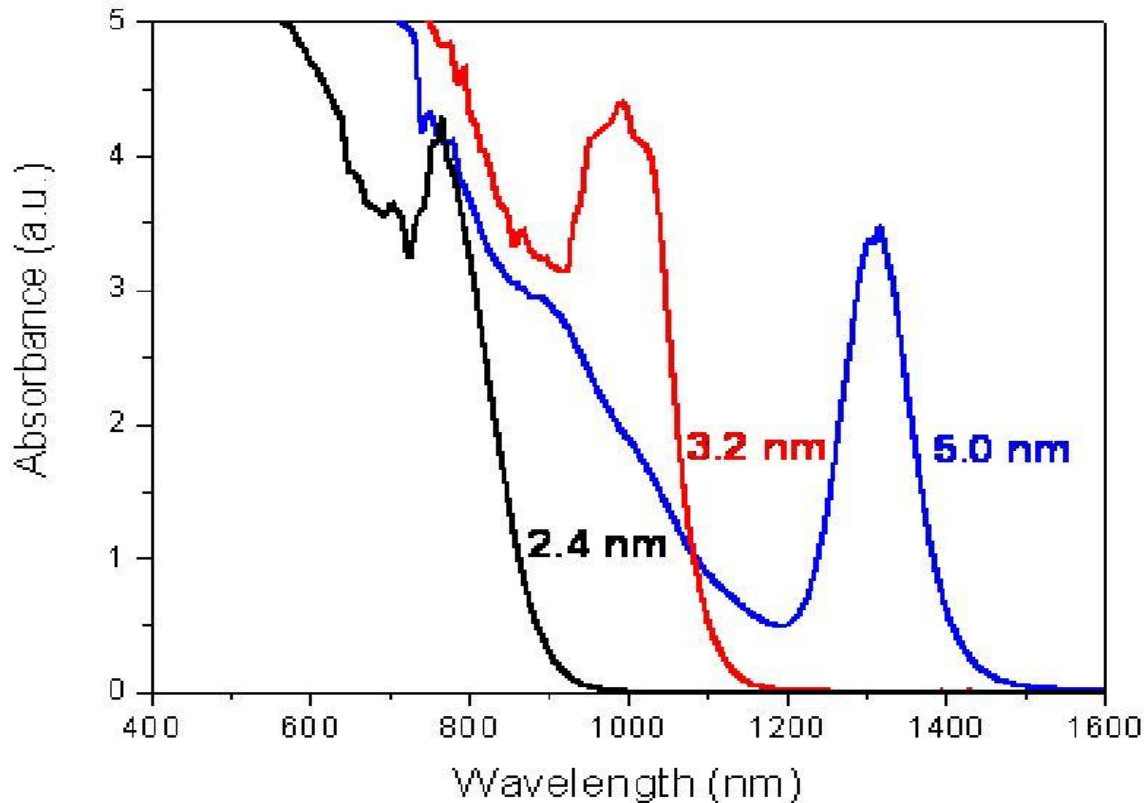


Fig 3.2: Measured absorbance of three different sizes PbS quantum dot suspended in toluene.

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 band gap materials expected to achieve maximum theoretical efficiency as high as 65%.

### 3.3 Multiple Exciton Generation in Semiconductor QDs:

Nozik and his coworkers [18-20] investigated Multiple exciton generation in semiconductor quantum dots. As illustrated in Figure 3.3, 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 band gap. In bulk semiconductor absorption of photon with energy exceeding the band gap 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.

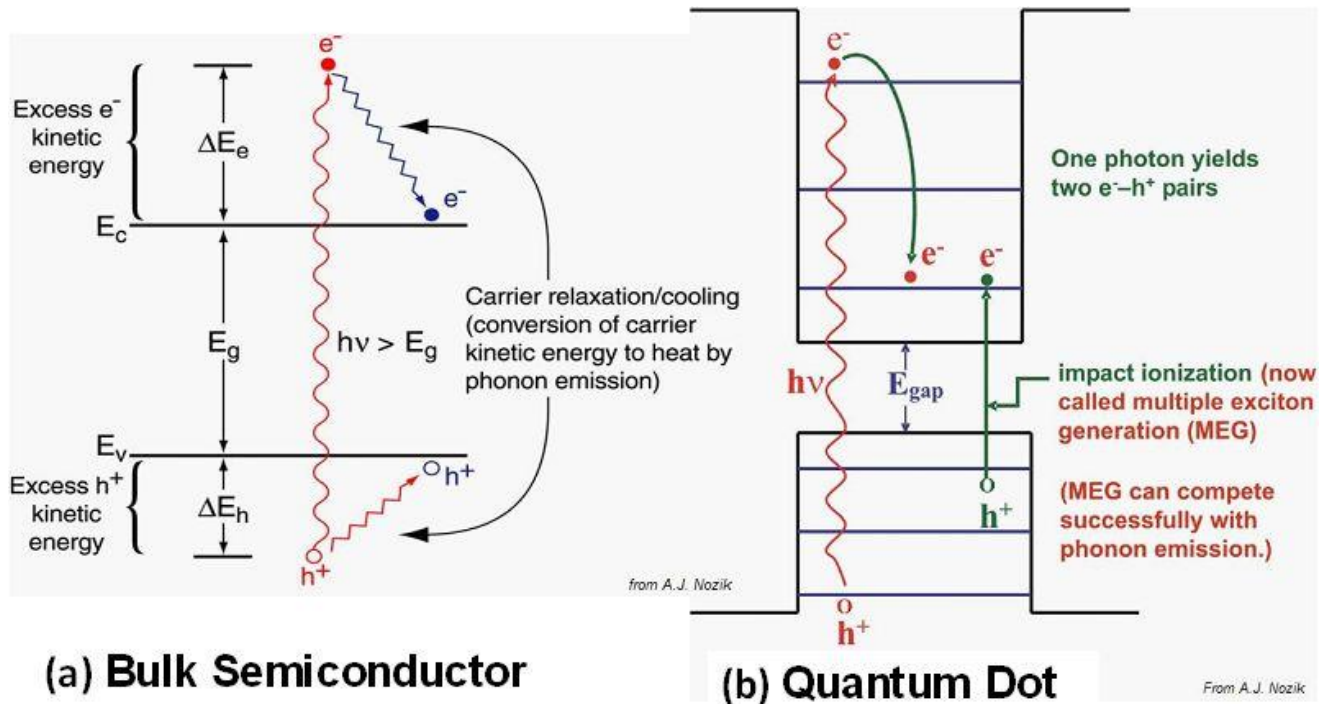


Fig 3.3: (a) Thermalization of hot carriers in a bulk semiconductor and (b) a quantum dot



### 3.4 Quantum dot Based Solar cell:

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 band gaps that are tunable across wide range energy levels by changing the dots' size. In bulk materials the band gap is fixed by the choice of material(s). 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 tunable by changing their size, which in turn defines the band gap. The dots can be grown over a range of sizes, allowing them to express a variety of band gaps without changing the underlying material or construction techniques [21]. A quantum dot solar cell makes infrared energy as accessible as any other [22]. 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.

Early examples used costly molecular beam epitaxy processes, but less expensive fabrication methods were later developed. These use wet chemistry (colloidal quantum dots – CQDs) and subsequent solution processing. Concentrated nanoparticle solutions are stabilized by long hydrocarbon ligands that keep the nanocrystals suspended in solution. To create a solid, these solutions are cast down and the long stabilizing ligands are replaced with short-chain crosslinkers. Chemically engineering the nanocrystal surface can better passivate the nanocrystals and reduce detrimental trap states that would curtail device performance by means of carrier recombination. This approach produces an efficiency of 7.0% [23]. In 2014 the use of iodide as a ligand that does not bond to oxygen was introduced. This maintains stable n- and p-type layers, boosting the absorption efficiency, which produced power conversion efficiency up to 8% [24] Solid state solar cell.

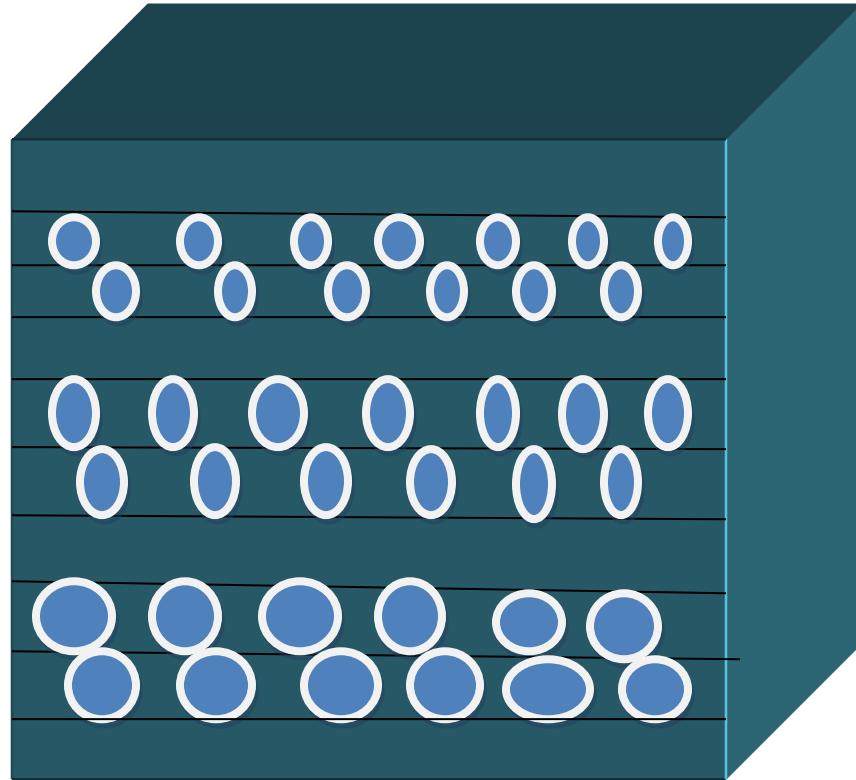


Fig 3.5: Quantum dot solar cell

### 3.5 Types of Quantum Dot Solar Cell:

There are many realistic quantum dots based solar cells. In this section we classify them in seven strategies just as an approach to fulfill the main objective of this chapter that is introducing quantum dot solar cells.

1. Schottky cell
2. Depleted heterojunction cell
3. Hybrid polymer cell
4. Quantum dot sensitized solar cell
5. Quantum dot-dye sensitized solar cell
6. P-i-n structure solar cell
7. QD Intermediate-Band solar cell

### 3.5.1 Schottky solar cell

The Schottky cell is a simple device in which an ultrathin film of colloidal QDs is sandwiched between two contacts for the extraction of photo generated electrons and holes. Typically, p-type QDs are employed supported on indium tin oxide (ITO) conducting glass, which acts as a contact for the extraction of carriers. A low work function metal is evaporated on the quantum dot layer. Charge transfer between the metallic contact and the QDs generates band bending in the QD layer together with a Schottky barrier that makes the contact selective. Schottky types of solar cells are attractive due to several reasons:

Firstly, they can be prepared by spray coating or inkjet printing from solution phase.

Secondly, thin layer ( $\sim 100$  nm) of absorber QDs is required in the photovoltaic cell.

So far, the Schottky devices have shown certain disadvantages as well.

First, many minority carriers (here electrons) must travel the entire film before reaching their destination electrode and are therefore more liable for recombination.

Second, in the Schottky device, the open-circuit voltage is often limited by Fermi-level pinning due to defect states at the metal–semiconductor interface. Such effects are important in photovoltaics as they limit the open-circuit voltage that a device can provide.

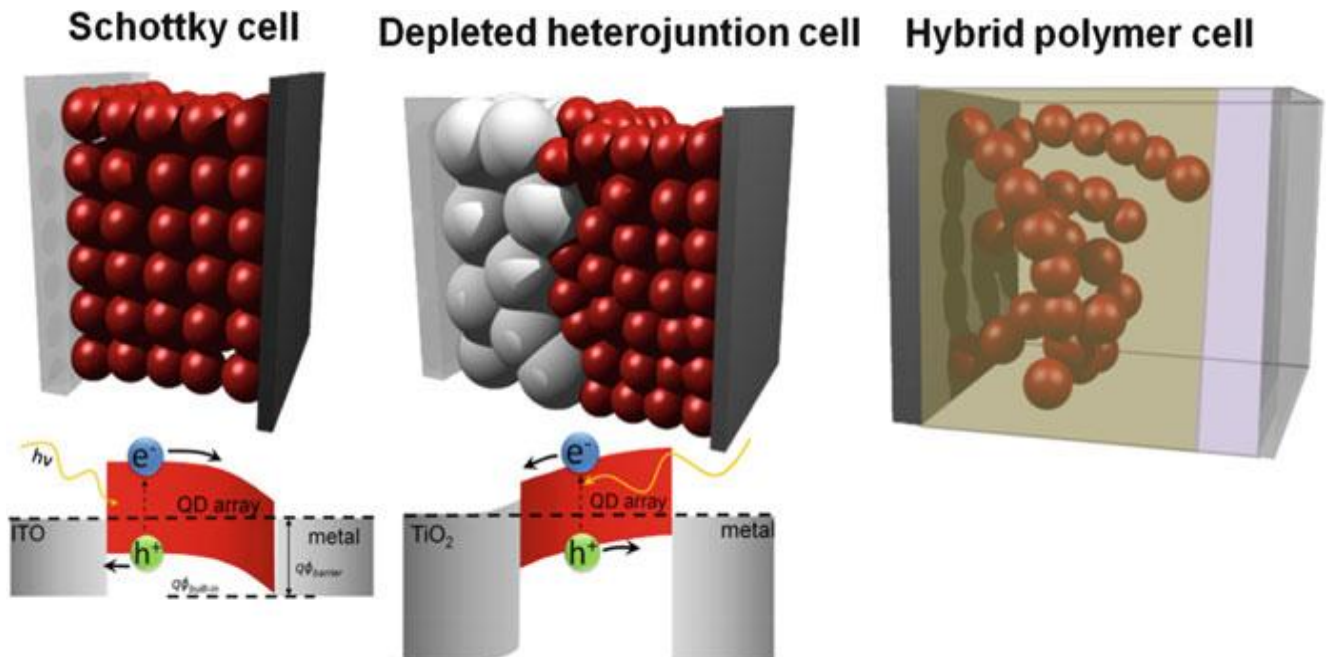


Fig 3.6: Sketches illustrating the different types of solar cells based on colloidal QDs

### 3.5.2 Depleted heterojunction cell

The depleted heterojunction cell consists of a nanostructured wide band gap oxide (TiO<sub>2</sub> or ZnO) supported on conducting glass. On top of this layer, a multilayer of QDs is deposited and the other contact of the device is provided by deposition of a metal (Au). The nanostructured oxide film acts as an electron conducting phase and helps the selective extraction of electrons from the QDs. In this case, the metal contact extracts the majority carriers. Although the photocurrents achieved in this case are smaller than for Schottky cells, improved open circuit voltages are obtained [25]. Another configuration that has been explored for more than 15 years is that of the so-called hybrid bulk heterojunction solar cell [26]. These cells are conceptually similar to the organic solar cells, although in this case the typical electron accepting phase would be substituted by QDs that would act as both electron transporting phase and light absorber (together with the polymer). These cells have given so far maximum conversion efficiencies substantially lower than those of the above-mentioned QD solar cells. This is probably due to the tendency to aggregation of the QDs and the lack of continuous pathways for the transport of charge. In addition, the design of the interface between the QDs and the hole conducting polymer is far from optimized. Importantly, all these cells are fabricated with colloidal QDs, being critical the quality of their surfaces.

Depleted heterojunction cells overcome the limitations of Schottky solar cells in several ways.

First, the depleted heterojunction design benefits from minority carrier separation due to the placement of the junction on the illumination side.

Second, back electron transfer from TiO<sub>2</sub> to QDs is suppressed by the built-in field of the depletion region.

Third, devices show improved open-circuit voltages due to better carrier separation at the QDs/TiO<sub>2</sub> interface

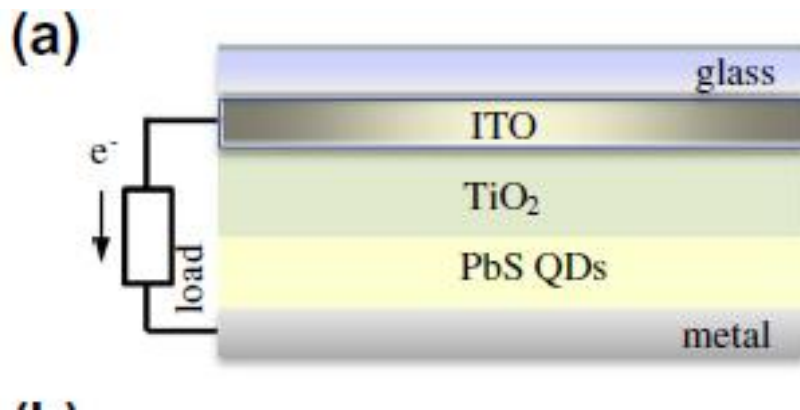


Fig 3.7: scheme of depleted heterojunction solar cell

### 3.5.3 Hybrid polymer cell/Bulk heterojunction polymer solar cell

Bulk heterojunction devices are composed of electron-donating conjugated polymers and electron- accepting fullerenes. The research on QDs in bulk heterojunction devices focuses on two aspects,

Firstly, QDs are used in bulk heterojunction devices in the presence of electron transporting fullerenes and hole conducting polymers (Feng et al., 2010; Arenas et al., 2010; Chen et al., 2008). QDs are added in the fullerene/polymer composite as light harvesting material.

Secondly, QDs are used in bulk heterojunction solar cells as light harvesting and simultaneously as electron transporting material (Wang et al., 2010a; Zhou et al., 2010).

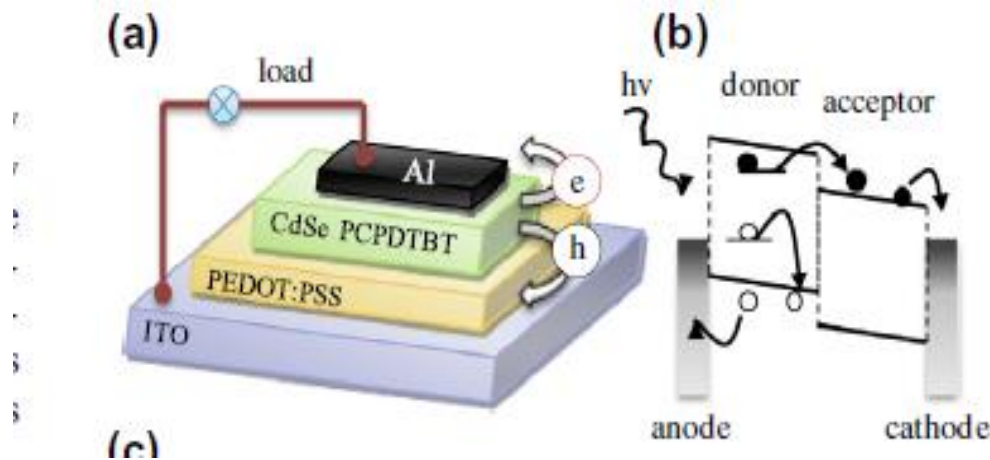


Fig 3.8: scheme of bulk heterojunction device

Fig 3.8 illustrates a scheme of a typical bulk heterojunction device composed of CdSe nanorods and hole conducting polymer PCPDTBT (Dayalet al., 2010a). Here the CdSe nanorods are used as electron acceptor material while PCPDTBT is used as donor phase. Unlike the polymer/fullerene bulk heterojunction cells where the fullerene contributes very little to the spectral response, the QDs based polymer solar cells offer an advantage for efficient light absorption. Current researches on QDs based bulk heterojunction solar cells are focused on several important points like: studies of phase segregation between the donor and the acceptor layers, studies to achieve controlled agglomeration of semiconductor nanocrystals in the polymer films, loading amount of nanocrystals in the polymer films, studies concerning the shape of the used nanocrystals, researches related to surface modifications of nanocrystals and finally studies which deal with new combinations of nanocrystals and polymers.



### 3.5.4 Quantum dot sensitized solar cell:

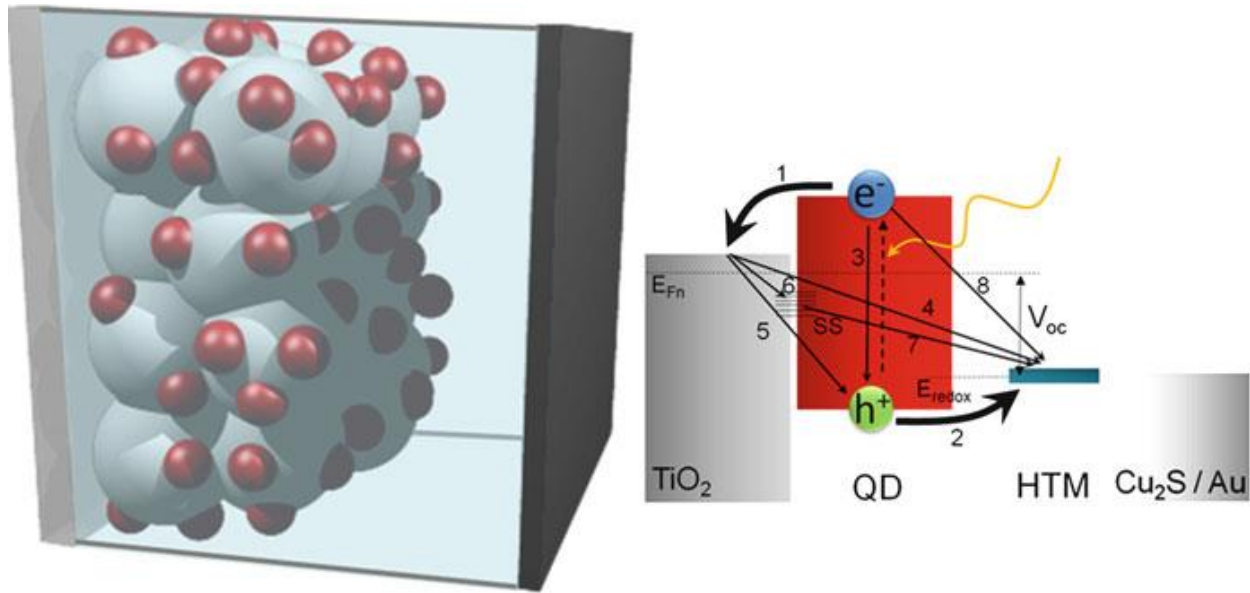


Fig 3.9: Sketch depicting a QDSSC and the corresponding energy-band diagram illustrating the main processes:

- (1) Electron injection;
- (2) Hole transfer to the HTM;
- (3) QD band-to-band recombination;
- (4) Recombination of TiO<sub>2</sub> CB electrons with the oxidized HTM;
- (5) Back electron transfer;
- (6) Electron trapping in interfacial states;
- (7) Recombination of TiO<sub>2</sub> trapped electrons with the oxidized HTM;
- (8) Recombination of QD CB electrons with the oxidized HTM

The QDSSCs follow an operational principle different from that of the previous devices, as in this case the QDs do not play the role of carrier transporting phase.

They could be considered as an offshoot of the ubiquitous dye-sensitized solar cells (DSSCs) appeared in 1991. In QDSSCs, QDs behave as light absorbers. Their photoexcitation leads to the generation of carriers that are selectively transferred to the surrounding phases. On the one hand, the photogenerated electrons are most commonly transferred to a wide band gap oxide (TiO<sub>2</sub>, SnO<sub>2</sub>, ZnO, etc.) on which the QDs are adsorbed. The electrons are finally extracted through the conducting glass that supports the nanostructured oxide. On the other hand, the photogenerated holes are transferred to either a liquid electrolyte or a solid hole transporting material (HTM) (Fig.3.9). In the first case, the electrolyte contains a reversible redox couple whose reduced

form accepts holes from the QDs. The counter electrode can be either a metal or a semiconductor electrode with a fast kinetics for the redox couple. The solid hole transporting phase is either a molecular material (such as 2, 20, 7, 70-tetrakis-(N,N-dipmethoxyphenylamine) 9,90-spirobifluorene, usually called spiro-OMeTAD) or a hole transporting conducting polymer, such as different polythiophenes. The contact for the extraction of holes is commonly a metal such as gold, forming an ohmic contact with the hole conducting phase. For the fabrication of these cells we may employ either presynthesized, colloidal quantum dots or alternatively, grow them on the nanostructured film. In the case of colloidal QDSSCs, several ways of attaching the QDs to the oxide structure have been employed. In some cases, the capped colloidal QDs self-assemble spontaneously on the nanostructured oxide layer (direct adsorption, DA) or are brought into contact with the oxide by electrophoresis.

Figure 3.9 summarizes the different recombination processes that may operate in these devices. On the one hand, we have the recombination in the quantum dot, which can be either band-to-band or mediated by band gap states (surface or interfacial states or traps). It is important to recognize that the QD/QD interfacial area will be much larger in the case of chemically grown quantum dots than in the case of colloidal quantum dots, where the typical coverages are smaller. Obviously, the recombination via surface states will also be different in the case of chemically deposited QDs, which are unprotected, and in that of colloidal QDs, which are typically capped. Another pathway for recombination occurs via the electrolyte (or HTM). In this case either the electrons in the QDs or those injected into the oxide can recombine with holes in the hole transporting phase, whether solid or liquid (in the case of a liquid electrolyte, the holes would be the oxidized species of the redox couple). In both cases, the electrons can be transferred from either the conduction band or surface states that capture electrons prior to their transfer to the hole transporting phase. When the electrons photogenerated in the QDs are directly involved in the recombination process, its rate is expected to strongly depend on the structure of the QD/electrolyte interface and thus on the QD nature.

Finally, recombination could occur between electrons injected in the oxide and holes remaining at the QDs (back electron transfer). The states at the interface between the oxide and the QDs could act as recombination centers. The density of these states is smaller in the case of colloidal QDs and, in addition, their nature should be different. This should also lead to different recombination characteristics in both cells [27].

Figure 3.10 shows an example of the obtained I-V characteristics of PdS quantum dots (size 3.2 nm) sensitized cell with power conversion efficiency = 1.8 %.

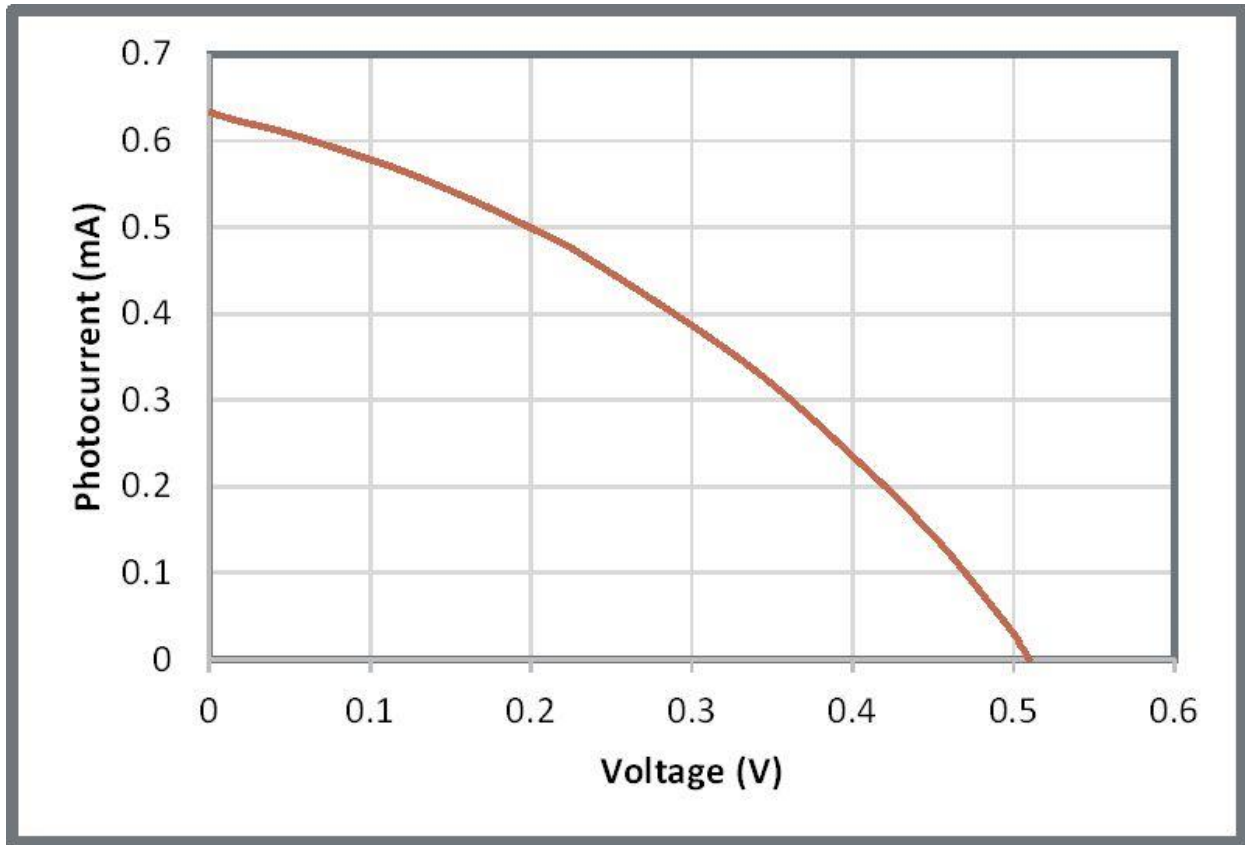


Fig 3.10: I-V characteristics of PbS quantum dot sensitized solar cell. Quantum dots have on the average radius of 3.2 nm.

### 3.5.5 Quantum dot-dye sensitized solar cell:

Incorporation of dye with quantum dots as sensitizer of wide bandgap semiconductor has attracted attention of any research groups. For example, we found that some natural dyes are enhancing power conversion efficiency, while some others are not. Figure 3.11 shows an example of the I-V characteristics of a first round study of assembled cells illuminated with a collimated beam from a hot filament lamp.

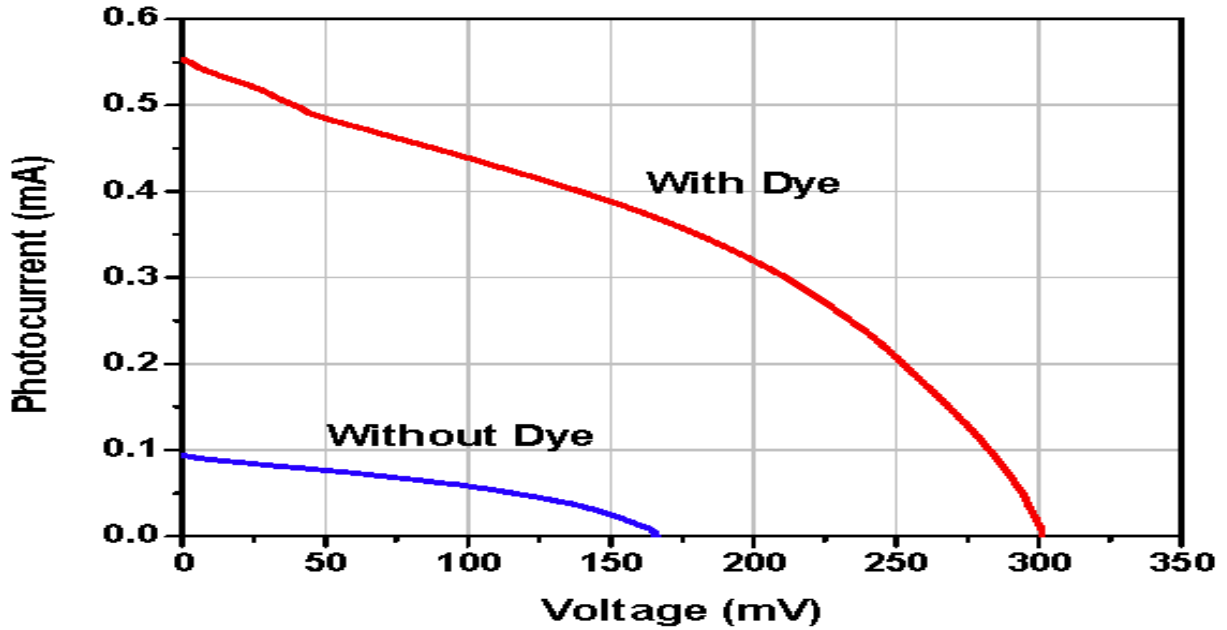


Fig 3.11: I-V characteristics of typical assembled quantum dot-dye sensitized solar cell. Quantum dots average size of 2.4 nm and pomegranate dye extract used as sensitizers of TiO<sub>2</sub> nanoporous layer.

New configuration based on quantum dot-dye bilayer-sensitized solar cells has been demonstrated by Zaban and co-workers [28]. The bi-sensitizer layer cell is made up of a nanocrystalline TiO<sub>2</sub>/CdS QD+amorphous TiO<sub>2</sub>/N719 dye. The main aim was to provide a configuration having increased charge-separation efficiency by slowing the interfacial charge recombination processes that resulted in 250% increase in cell efficiency compared to a QD monolayer cell. The configuration investigated by Zaban and co-workers [29] established on making colloidal quantum dots (CdSe/CdS/ZnS core/shell/shell quantum dots) that serve as antennas. Via nonradiative energy transfer, absorbed light is funneled to the charge separating dye molecules (SQ02 dye molecules). The colloidal quantum dot donors are incorporated into the solid TiO<sub>2</sub> photoelectrode resulting in high energy transfer efficiency as well as substantial improvement of the cell stability.

In this approach the processes of light absorption can be separated from charge carrier injection. This approach enables optimization of each independently. Time resolved luminescence measurements relate the significant contribution of the QDs to the spectral response of the cell in the presence of the dye to Förster resonance energy transfer from the QDs to the dye molecules.

The efficiency of solar cells can be enhanced by combining quantum dots with some dye and used as a sensitizer. We suggest doing further investigations in order to understand QD-dye system. The performance of dye sensitized or quantum dots solar cells can be increased by optimizing preparation technique, using different types of electrolyte,

utilizing different nanostructures (e.g., rods, stars), and replacing TiO<sub>2</sub> with other types of wide bandgap semiconductors such as zinc oxide ZnO.

### 3.5.6 P-i-n structure solar cell:

Nozik and his coworkers [30, 31] suggested a general p-i-n junction configuration for incorporating array of QDs into solar cells. QDs array forms the active medium of the cell (the intrinsic region). In this arrangement quantum size effects should not be eradicated due to cell architecture, excitons must be separated prior to Auger recombination, and upon absorption of photon excitons ought to be separated into free-charge carriers and transported to appropriate electrodes.

Fig 3.12 shows quantum dot layers forming the i-region of a solar cell. The QDs are electronically coupled to each other to sustain electron and hole transport. Also, minibands are formed and hence could facilitate intermediate band formation. Intermediate energy band is energy absorbing band which can accept electron excitations from the valance band and then allow transitions to the conduction band. In quantum dots solar cells with intermediate bands photon of energies lower than the bandgap are basically absorbed and high energy photons produce hot-carriers (see Figure 3.12). Collecting charge-carriers while they are hot enhances cell voltage. On the other hand, photocurrent enhancement could be achieved by getting more from the hot-carriers via inverse Auger recombination (impact ionization) leading to multiple exciton generation MEG. One needs to bear in mind electron tunneling mechanism between quantum dots.

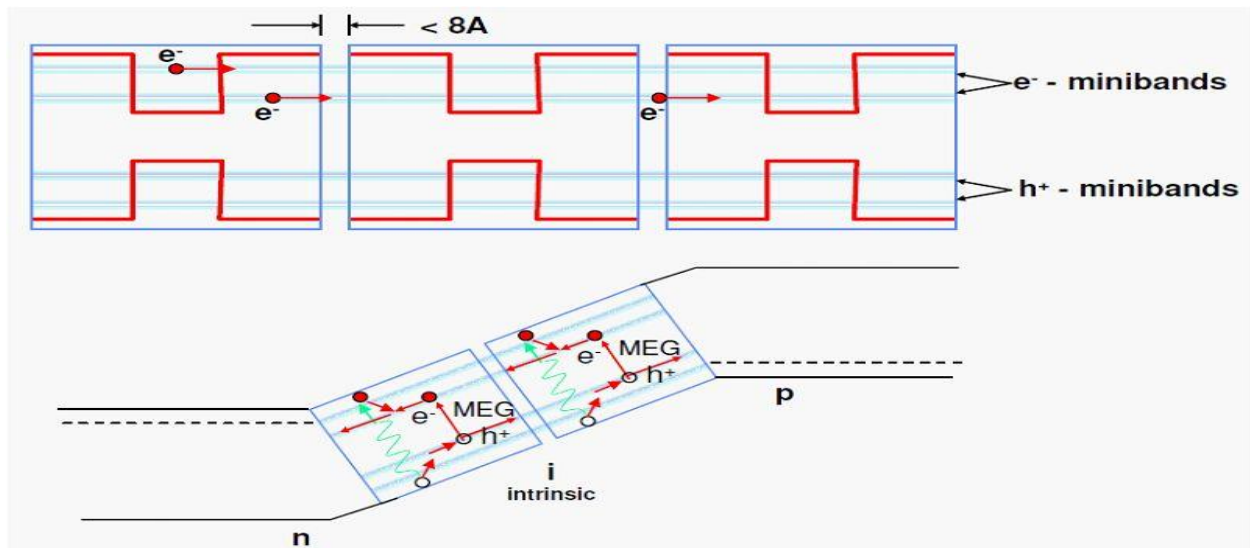


Fig 3.12: Possible p-i-n QD arrangements for solar cells.

### 3.5.7 QD Intermediate-Band solar cell:

QDs have been proposed as one of the means of manufacturing the IB solar cell. In this respect, the IB would arise from the confined electronic states of the electrons in the potential wells of the conduction band (Figure 3.13).

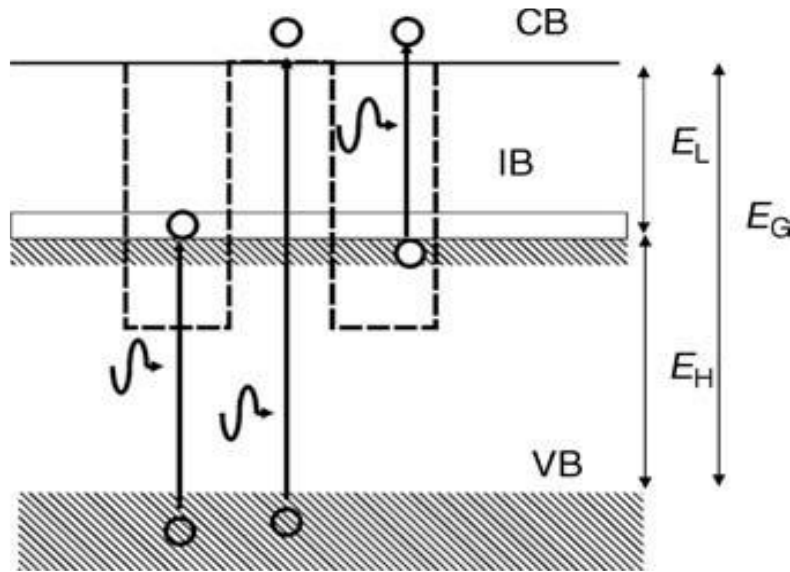


Fig 3.13: Structure of an intermediate band (IB) material, showing the possible optical transitions. The dashed lines in the bandgap ( $E_G$ ) represent the formation of the IB from an array of quantum dots. CB is conduction band, VB is valence band.

QDs have the potential to truly isolate the intermediate band from the conduction band by means of a zero density of states. Actually, it is this isolation that is considered to be responsible for the controversial “phonon bottleneck” effect through which a transition from the CB to the IB is believed to be inhibited because of the low probability of simultaneous multiphonon interactions with electrons needed to bridge the energy difference between the CB and the IB. To facilitate the absorption of photons that cause transitions from the IB to the CB, the IB must be half - filled with electrons so that there are enough electrons to have a reasonable rate of electron promotion from the IB to the CB. This can be accomplished through n type modulation doping of the barrier region between dots at an approximate concentration that equals the dot concentration.

The basic structure of QD-IB solar cell prototype cells consists of 10 layers of InAs/GaAs QDs sandwiched by p and n GaAs emitters and grown by molecular beam epitaxy in the Stranski-Krastanov growth mode.

Figure 3.14 shows a typical current–voltage characteristic compared with that of a test GaAs sample. As can be seen, the photo generated current appears to be approximately the same.

However, an examination of the quantum efficiency of the cells (Figure 3.15) reveals this is not the case.

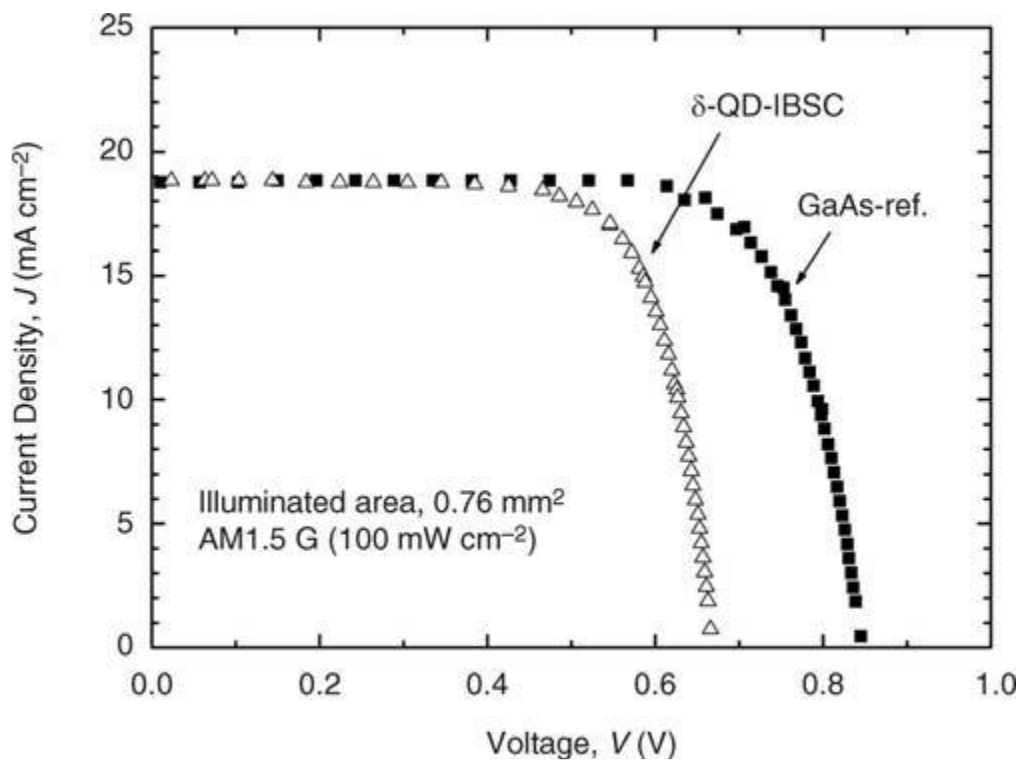


Fig 3.14: Current–voltage characteristic of a QD intermediate-band solar cell (IBSC) and a reference GaAs solar cell.

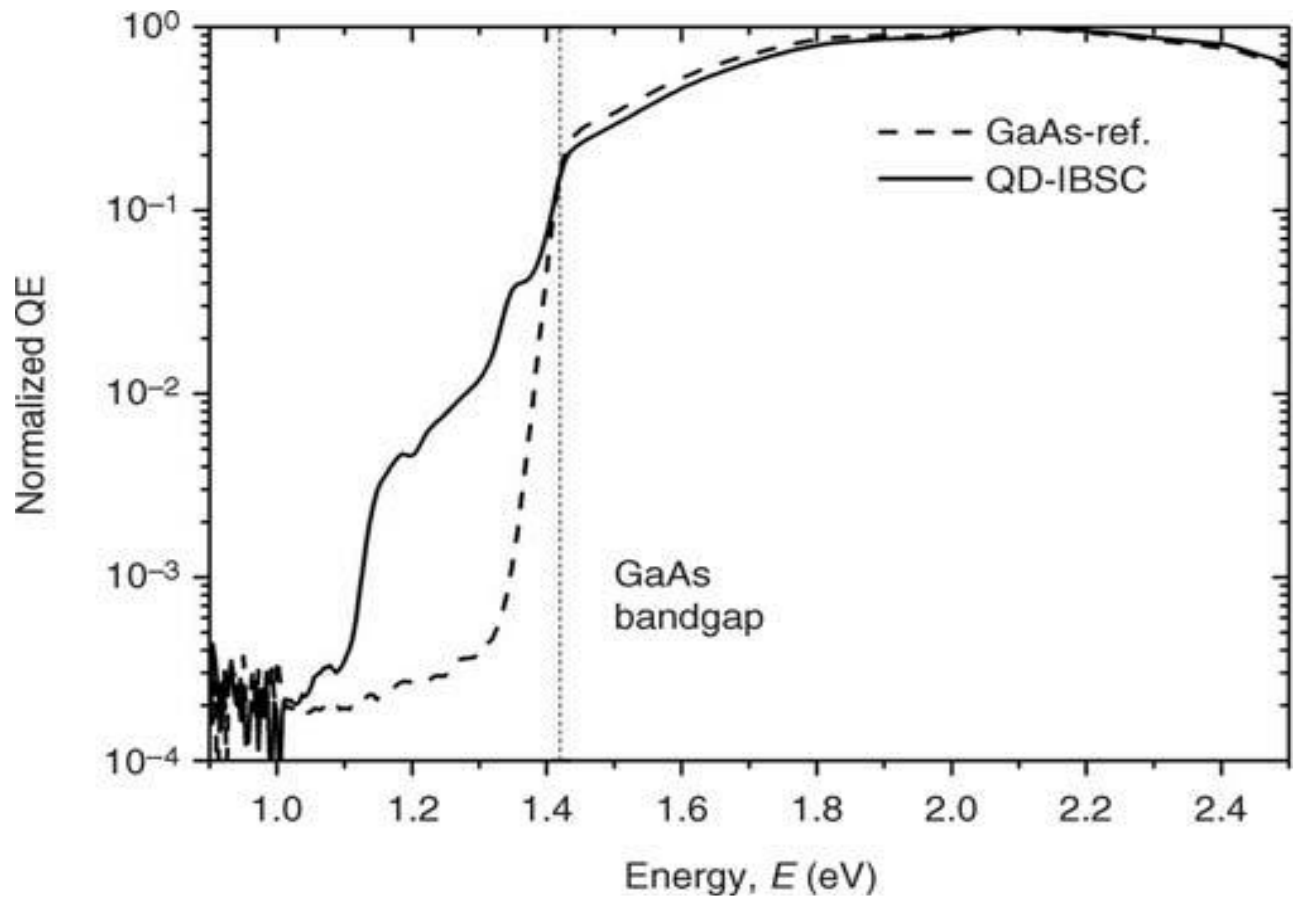


Fig 3.15: Normalized quantum efficiency (QE) of a QD intermediate-band solar cell (IBSC) compared with that of a reference GaAs solar cell.



## Chapter 4

### Analyses of Quantum dot solar cell spectrum

#### 4.1 Introduction:

**Sunlight** is a portion of the electromagnetic radiation given off by the Sun, in particular infrared, visible and ultraviolet light. On Earth, sunlight is filtered through Earth's atmosphere, and is obvious as daylight when the Sun is above the horizon. When the direct solar radiation is not blocked by clouds, it is experienced as **sunshine**, a combination of bright light and radiant heat. When it is blocked by the clouds or reflects off other objects, it is experienced as diffused light

#### 4.2 Quantum dot solar cell spectrum:

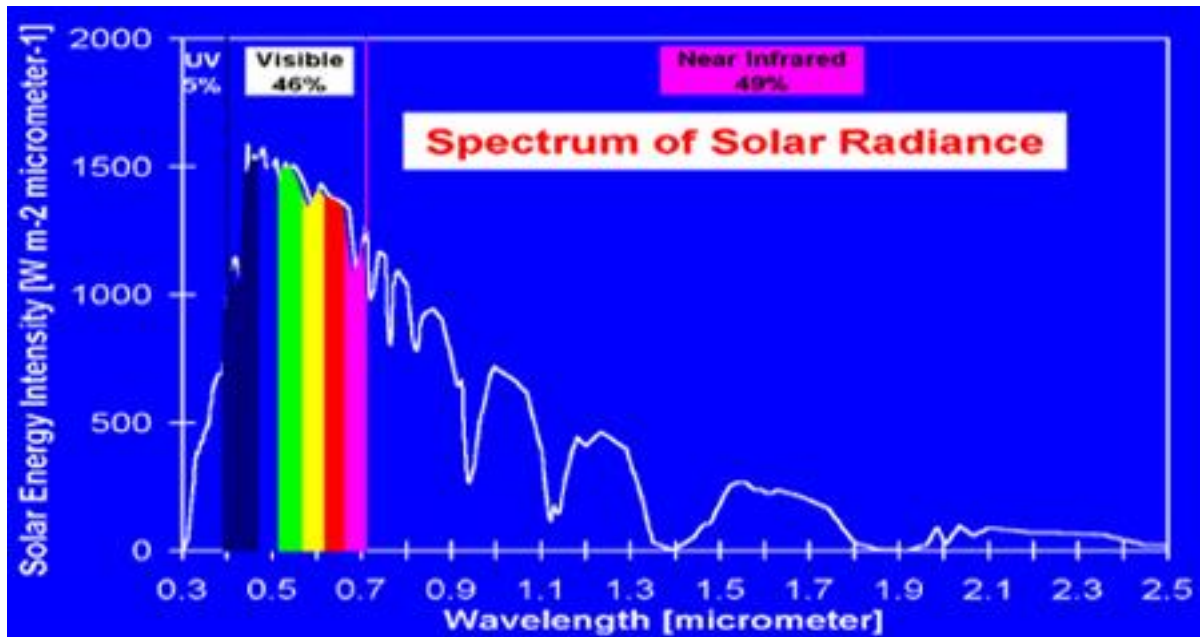


Fig 4.1: Quantum dot solar cell spectrum

Shown in the diagram on the left is how the energy from the sun is distributed by wavelength and photon energy. As one can see, a good portion of the sun's radiation is in the visible range (46%). Radiation in the ultraviolet region (5%), which is not visible, causes the skin to tan and has more energy than that in the visible region. Radiation in the infrared region (49%), which we feel as heat, has slightly more total energy than the radiation in the visible region.

The shape of the spectrum is almost a perfect fit for a heavenly body whose temperature is 5,800 K. This is how we know with good accuracy the temperature at the sun's surface. Other stars have enormous sources of energy in the form of high energy X-rays, but lucky for us, our sun releases almost half of its energy as visible light.

### **4.3 Element Properties of Quantum dot solar cell:**

Quantum dot solar cell can capture all the solar spectrum but In this section we discussed about 5 types of important element which also capture solar radiation spectrum as shown in Figure 4.1

5 types of elements are:

- Indium antimonide (InSb)
- Indium arsenide (InAs)
- Lead sulfide (PbS)
- Lead selenide (PbSe)
- Lead Telluride (PbTe)

#### **4.3.1 Indium antimonide:**

Indium antimonide (InSb) is a crystalline semiconductor made of antimony and indium. It belongs to the III-V group and is a narrow gap semiconductor material. Detectors made of indium antimonide are sensitive and lie between a wavelength of 1 and 5  $\mu\text{m}$ . Indium antimonide was commonly used in mechanically scanned single detector thermal imaging systems.

## Electrical Properties

The electrical properties of indium antimonide are provided in the table below:

Electrical Properties	
Intrinsic Carrier Concentration	$2 \times 10^{16} \text{ cm}^{-3}$
Electron Mobility	$\leq 7.7 \times 10^4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$
Hole Mobility	$\leq 850 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$
Electron Diffusion Coefficient	$\leq 2 \times 10^3 \text{ cm}^2 \text{ s}^{-1}$
Hole Diffusion Coefficient	$\leq 22 \text{ cm}^2 \text{ s}^{-1}$
Electrical resistivity	$4 \times 10^{-13} \Omega \text{ cm}$

## Thermal, Mechanical and Optical Properties

The thermal, mechanical and optical properties of indium antimonide are provided in the tables below:

Mechanical Properties	
Melting Point	527 °C
Density	$5.775 \text{ g cm}^{-3}$
Bulk Modulus	$4.7 \cdot 10^{11} \text{ dyn cm}^{-2}$

Thermal Properties	
Thermal Conductivity	$0.18 \text{ W cm}^{-1} \text{ }^\circ\text{C}^{-1}$
Thermal Diffusivity	$0.16 \text{ cm}^2 \text{ s}^{-1}$
Thermal Expansion Coefficient	$5.37 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$

Optical Properties	
Refractive Index (589 nm @ 293 K)	4

### 4.3.2 Indium arsenide:

Indium arsenide, InAs or indium monoarsenide, is a semiconductor composed of indium and arsenic. It has the appearance of grey cubic crystals with a melting point of 942 °C. It is a direct band gap material. InAs is well known for its high electron mobility and narrow energy band gap.

#### Basic Parameters at 300 K

Crystal structure	Zinc Blende
Group of symmetry	$T_d^2-F43m$
Number of atoms in 1 cm <sup>3</sup>	$3.59 \cdot 10^{22}$
de Broglie electron wavelength	400 Å
Debye temperature	280 K
Density	$5.68 \text{ g cm}^{-3}$
Dielectric constant (static)	15.15
Dielectric constant (high frequency)	12.3
Effective electron mass	$0.023m_0$
Effective hole masses $m_h$	$0.41m_0$
Effective hole masses $m_{lp}$	$0.026m_0$
Electron affinity	4.9 eV

Lattice constant 6.0583 Å

Optical phonon energy 0.030 eV

### **Electrical properties**

Breakdown field  $\approx 4 \cdot 10^4 \text{ V cm}^{-1}$

Mobility of electrons  $\leq 4 \cdot 10^4 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$

Mobility of holes  $\leq 5 \cdot 10^2 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$

Diffusion coefficient of electrons  $\leq 10^3 \text{ cm}^2 \text{s}^{-1}$

Diffusion coefficient of holes  $\leq 13 \text{ cm}^2 \text{s}^{-1}$

Electron thermal velocity  $7.7 \cdot 10^5 \text{ m s}^{-1}$

Hole thermal velocity  $2 \cdot 10^5 \text{ m s}^{-1}$

### **Optical properties**

Infrared refractive index  $\approx 3.51$  (300 K)

Radiative recombination coefficient  $1.1 \cdot 10^{-10} \text{ cm}^3/\text{s}$

### **Thermal properties**

Bulk modulus  $5.8 \cdot 10^{11} \text{ dyn cm}^{-2}$

Melting point 942 °C

Specific heat  $0.25 \text{ J g}^{-1} \text{ °C}^{-1}$

Thermal conductivity  $0.27 \text{ W cm}^{-1} \text{ °C}^{-1}$

Thermal diffusivity  $0.19 \text{ cm}^2 \text{s}^{-1}$

### 4.3.3 Lead sulfide:

Lead sulfide is an inorganic compound with the chemical formula PbS. It is also known as galena, which is the principal ore and important compound of lead. It is one of the earliest materials to be used as a semiconductor as it tends to crystallize in sodium chloride. Lead sulfide is toxic if it is heated to decomposition, which forms lead and sulfur oxides.

#### Chemical Properties

The chemical properties of lead sulfide are provided in the table below:

Chemical Properties	
Chemical Formula	PbS
Molecular Weight	239.30
CAS No.	1314-87-0
Group	Lead-14 Sulfur - 16
Crystal Structure	Cubic
Symmetry Group	Fm3m
Lattice Constant	5.936 Å

#### Electrical Properties

The electrical properties of lead sulfide are provided in the table below:

Electrical Properties	
Magnetic Susceptibility	-0.0000836

Band Gap	0.37 eV
Electron Mobility	600 cm <sup>2</sup> /Vs
Hole Mobility	600 cm <sup>2</sup> /Vs

### Thermal, Mechanical and Optical Properties

The thermal, mechanical and optical properties of lead sulfide are provided in the tables below:

Thermal Properties	
Heat of Fusion	72 J/g
Heat of Formation	435 kJ/mol
Thermal Conductivity	2.30 W/mK
Mechanical Properties	
Density	7.61 g/cm <sup>3</sup>
Melting Point	1117°C
Mohs Hardness	2.5
Optical Properties	
Refractive Index	3.91

#### 4.3.4 Lead selenide:

Lead selenide is a semiconductor material that forms cubic crystals similar to the structure of NaCl . It performs efficiently at low temperatures, without the need for cooling. It naturally occurs in the mineral clausthalite and can be formed by a direct

reaction between lead and selenium. Its peak sensitivity depends on temperature and varies between 3.7 and 4.7 $\mu\text{m}$ .

### Chemical properties

Chemical Formula	PbSe
Molecular Weight	286.16
Group	Lead – 14 Selenium – 16
Crystal Structure	Cubic
Lattice Constant	6.1243 Å

### Electrical Properties

The electrical properties of lead selenide are provided in the table below:

Band Gap	0.26 eV
Electron Mobility	1000 cm <sup>2</sup> /Vs
Hole Mobility	900 cm <sup>2</sup> /Vs

### Thermal and Mechanical Properties

The thermal and mechanical properties of lead selenide are provided in the tables below:

#### Thermal properties

Heat of Formation	393 kJ/mol
Thermal Conductivity	1.70 W/mK



## Mechanical properties

Density 8.15 g/cm<sup>3</sup>

Melting Point 1067°C

### 4.3.5 Lead Telluride:

Lead Telluride is a compound of lead and tellurium (PbTe). It is a narrow gap semiconductor with a band gap of 0.32 eV.

Chemical Properties	
Chemical Formula	PbTe
Molecular Weight	334.8
Group	Lead – 14 Tellurium - 16
Crystal Structure	Cubic
Lattice Constant	6.454 Å
Electrical Properties	
Band Gap	0.25 eV
Electron Mobility	1600 cm <sup>2</sup> /Vs
Hole Mobility	600 cm <sup>2</sup> /Vs
Thermal Properties	
Heat of Formation	393 kJ/mol

Thermal Conductivity	2.30 W/mK
<b>Mechanical Properties</b>	
Density	8.16 g/cm <sup>3</sup>
Melting Point	907°C
Mohs Hardness	3

## Chapter 5

### Result:

#### InSb

Electron  $m_e = 0.014m_0$

Hole  $m_h = 0.42m_0$

Energy band gap (bulk)  $E_g(\text{bulk}) = 0.17\text{eV}$

So effective mass is  $m_{eff} = (m_e \times m_h) \div (m_e + m_h)$   
 $= 0.0135 m_0$

We know,

$$E_g(\text{QD}) = E_g(\text{bulk}) + \frac{h^2}{8R^2 m_{eff}} \quad \text{-----} \quad (5.1)$$

$$\gg 4.13 = 0.17 + \frac{h^2}{8R^2 m_{eff}}$$

$$\gg 3.96 = \frac{1}{R^2} (4.39 \times 10^{-67}) \div (8 \times 0.0135 \times 9.1 \times 10^{-31} \times 1.6 \times 10^{-19})$$

$$\gg R^2 3.96 = 4.39 \times 10^{-67} \div 1.51 \times 10^{-50}$$

$$\gg R^2 = 7.34 \times 10^{-18}$$

$$\gg R = \sqrt{(7.34 \times 10^{-18})}$$

$$\text{So } R = 2.7 \times 10^{-9} \text{m} = 2.7 \text{nm}$$

Now we can calculate the entire wavelength as shown in fig 34 and find the different size of InSb

We also know,

$$E_g = \{1.24 \div \lambda(\mu\text{m})\} \text{eV} \quad \text{-----} \quad (5.2)$$

**Table 1:**

The size of **InSb** are provided in the table below

$\lambda(\mu\text{m})$	$E_g(\text{ev})$	InSb R
0.3	4.13	2.7nm
0.4	3.1	1.58nm
0.5	2.48	1.78nm
0.6	2.06	1.97nm
0.7	1.77	2.14nm
0.8	1.55	2.31nm
0.9	1.37	2.47nm
1.0	1.24	2.62nm
1.1	1.13	2.76nm
1.2	1.03	2.92nm
1.3	0.95	3.06nm
1.4	0.88	3.22nm
1.5	0.83	3.33nm
1.6	0.77	3.49nm
1.7	0.73	3.62nm
1.8	0.68	3.79nm
1.9	0.65	3.91nm
2.0	0.62	4.03nm
2.1	0.59	4.18nm
2.2	0.56	4.33nm
2.3	0.53	4.52nm
2.4	0.52	4.58nm
2.5	0.49	4.78nm

**Table 2: InAs**

Similarly we can calculate the size of InAs as shown in equation (5.1) & (5.2)

$\lambda(\mu\text{m})$	$E_g(\text{eV})$	InAs R
0.3	4.13	2.02nm
0.4	3.1	2.37nm
0.5	2.48	2.69nm
0.6	2.06	3.00nm
0.7	1.77	3.3nm
0.8	1.55	3.6nm
0.9	1.37	3.89nm
1.0	1.24	4.16nm
1.1	1.13	4.45nm
1.2	1.03	4.76nm
1.3	0.95	5.07nm
1.4	0.88	5.40nm
1.5	0.83	5.67nm
1.6	0.77	6.06nm
1.7	0.73	6.37nm
1.8	0.68	6.84nm
1.9	0.65	7.17nm
2.0	0.62	7.56nm
2.1	0.59	8.02nm
2.2	0.56	8.58nm
2.3	0.53	9.3nm
2.4	0.52	9.53nm
2.5	0.49	10.5nm

**Table 3: PbS**

$\lambda(\mu\text{m})$	$E_g(\text{eV})$	PbS R
0.3	4.13	1.73nm
0.4	3.1	1.05nm
0.5	2.48	1.206nm
0.6	2.06	1.35nm
0.7	1.77	1.49nm
0.8	1.55	1.63nm
0.9	1.37	1.77nm
1.0	1.24	1.91nm
1.1	1.13	2.05nm
1.2	1.03	2.21nm
1.3	0.95	2.37nm
1.4	0.88	2.55nm
1.5	0.83	2.71nm
1.6	0.77	2.93nm
1.7	0.73	3.11nm
1.8	0.68	3.39nm
1.9	0.65	3.61nm
2.0	0.62	3.87nm
2.1	0.59	4.20nm
2.2	0.56	4.63nm
2.3	0.53	5.22nm
2.4	0.52	5.47nm
2.5	0.49	6.54nm

**Table 4: PbSe**

$\lambda(\mu\text{m})$	$E_g(\text{ev})$	PbSe R
0.3	4.13	0.78nm
0.4	3.1	0.91nm
0.5	2.48	1.03nm
0.6	2.06	1.14nm
0.7	1.77	1.25nm
0.8	1.55	1.35nm
0.9	1.37	1.46nm
1.0	1.24	1.55nm
1.1	1.13	1.65nm
1.2	1.03	1.75nm
1.3	0.95	1.85nm
1.4	0.88	1.96nm
1.5	0.83	2.04nm
1.6	0.77	2.16nm
1.7	0.73	2.26nm
1.8	0.68	3.00nm
1.9	0.65	2.48nm
2.0	0.62	2.59nm
2.1	0.59	2.70nm
2.2	0.56	2.84nm
2.3	0.53	3.006nm
2.4	0.52	3.06nm
2.5	0.49	3.27nm

**Table 5: PbTe**

$\lambda(\mu\text{m})$	$E_g(\text{eV})$	PbTe R
0.3	4.13	1.03nm
0.4	3.1	1.20nm
0.5	2.48	1.37nm
0.6	2.06	1.53nm
0.7	1.77	1.67nm
0.8	1.55	1.82nm
0.9	1.37	1.96nm
1.0	1.24	2.10nm
1.1	1.13	2.24nm
1.2	1.03	2.39nm
1.3	0.95	2.54nm
1.4	0.88	2.69nm
1.5	0.83	2.82nm
1.6	0.77	3.00nm
1.7	0.73	3.15nm
1.8	0.68	3.36nm
1.9	0.65	3.51nm
2.0	0.62	3.68nm
2.1	0.59	3.88nm
2.2	0.56	4.12nm
2.3	0.53	4.40nm
2.4	0.52	4.51nm
2.5	0.49	4.89nm



**Discussion:**

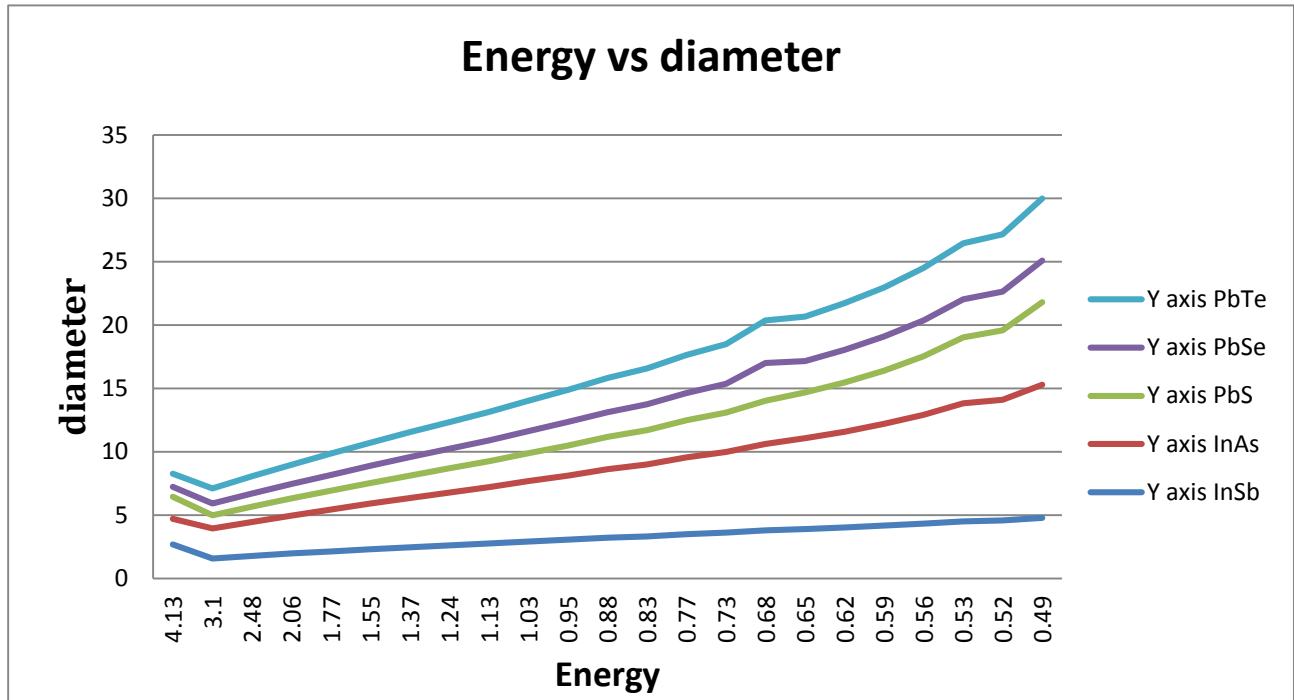


Fig 5.1: The graph of Energy Vs diameter

This work we have found 5 materials to be used as QD materials for capturing the solar energy based on the modified Brus equation

$$\Delta E(r) = E_{\text{gap}} + \frac{h^2}{8r^2} (1/m_e^* + 1/m_h^*) . \dots\dots\dots (5.3)$$

We calculate the diameter for different wavelength of the solar spectrum from 0.3 to 2.5 and calculation based on the equation

$$E_g(\text{QD}) = E_g(\text{bulk}) + h^2 \div 8R^2 m_{\text{eff}} \text{ and } E_g = \{1.24 \div (\mu\text{m})\} \text{ ev } \dots\dots\dots (5.4)$$

We calculate the diameter of different materials QDs ( InSb, InAs, PbS, PbSe and PbTe) for absorbing the total solar spectrum and results are given from Table 1 to Table 5 and

The energy vs diameter of different materials QDs are shown in Fig(5.1) and it is found that to observing the total solar spectrum for **InSb** material we need minimum size.

## Chapter 6

### Conclusion and Future work

#### 6.1 conclusions:

In this report, we have described the fundamentals of Quantum dot solar cell including solar radiation, different types of Quantum dot based solar cell and Elementary properties of Quantum dot solar cell. It is well known that The relaxation dynamics of photo excited excitons in semiconductor quantum dots can be greatly modified compared with the relaxation dynamics of free electron–hole pairs formed in bulk semiconductors. Different types of configurations for QD solar cells are described here that could produce enhanced photocurrent and the thermodynamic efficiencies for these new types of solar cells have been calculated. And it is obvious that some material can be used to fabricate the QD based solar cell spectrum .We have studied 5 semiconductor materials such as InAs, InSb, PbS, PbSe, PbTe and which can captured all solar radiation spectrum.

#### 6.2 Future Work:

Amongst the semiconductor materials, PbS has direct bandgaps of 0.37 eV. PbS has a cutoff for light absorption till 3357 nm in the solar spectra and a large Bohr radius of 18 nm. The large Bohr radius makes PbS one of the most attractive QDs since the onset of absorption can be tuned to blue shifted from 3357 nm (0.37 eV) to around 620 nm (~2 eV) covering the IR part of the solar spectrum which is largely unutilised. PbS nanoparticles have also been reported to demonstrate multiple exciton generation (MEG) Higher surface coverage and homogeneous distribution of PbS quantum dots deposited by SILAR has been identified as a bottleneck for achieving higher efficiencies. Research on CdSe/PbS, CdTe/PbS dual-sensitisers structures are likely to pave the way for highest QDSC conversion efficiencies.

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