ANALYSIS OF PHOTONIC CRYSTALS BASED SOLAR CELLS

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In

VLSI Design and CAD

Submitted By

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DECLARATION

I hereby declare that the work which is being presented in the dissertation entitled, "**Analysis of Photonic Crystals Based Solar Cells**" in partial fulfilment of the requirement for the award of degree of Master of Technology in VLSI Design & CAD submitted in Electronics and Communication Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Dr. Mukesh Kumar, Assistant Professor, ECED and refers other researcher's work which are duly listed in the reference section.

The matter presented in this dissertation has not been submitted in any other University/Institute for the award of degree.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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Varun Sadana

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ABSTRACT

A solar cell with a photonic crystal has been analysed. A periodic structure has been created on top layer of organic solar cell which act as a photonic crystal. Photonic crystals can enhance the efficiency of a solar cell. Before studying the absorption enhancement of Photonic crystal organic solar cell (PCOSC), the thickness of the optical spacer "nc-ZnO" of the flat solar cell has been optimized so that the absorption enhancement of PCOSC in comparison with the flat solar cell can be evaluated.. Light absorption of 1D PCOSC has also been calculated and the absorption enhancement by the PC structure has been shown in the report. For reference, the light absorption of the PCOSC has been first calculated when ITO and PEDOT:PSS are assumed to be perfectly transparent so that the resonant-like sharp absorption caused by the leaky mode can be clearly observed. Although the sharp effect for the TE polarization cannot be seen any more, the enhancement for TM polarization has been observed. It has also been observed that the location and magnitude of optical absorption varies strongly with wavelength on account of strong frequency dependence of photonic crystal structure.

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ABBREVIATIONS

DBR	Distributed Bragg reflectors
DC	Direct Current
FCC	Face-centered Cubic
FDTD	Finite Difference Time Domain
FF	Fill Factor
GPS	Global Positioning System
HOMO	Highest Occupied Molecular Orbital
IR	Infrared
ITO	Indium Tin Oxide
LUMO	Lowest Unoccupied Molecular Orbital
MCM	Multi-coefficient Model
OPVC	Organic Photovoltaic Cell
OSC	Organic Solar Cell
P3HT:PCBM	Poly-3-Hexylthiophene Phenyl-C61 Butyric acid Methyl ester
PC	Photonic Crystal
PCOSC	Photonic Crystal Organic Solar Cell
PEDOT:PSS	Poly 3,4-ethylenedioxythiophene- Poly 4-styrenesulfonate
PML	Perfectly Matched Layer
PV	Photovoltaic
R_S	Series Resistance
R_{SH}	Shunt Resistance
TE	Transverse-electric
TM	Transverse-magnetic
UV	Ultraviolet
VCSEL	Vertical Cavity Surface Emitting Lasers

CHAPTER 1
INRODUCTION TO SOLAR CELLS

1.1 INTRODUCTION

Solar cell is basically a semiconductor structure that converts solar energy into electrical energy, either directly via the photovoltaic effect, or indirectly by first converting the solar energy to heat or chemical energy.

The most common form of solar cells are based on the *photovoltaic (PV) effect* in which light falling on a two layer semi-conductor device produces a photo voltage or potential difference between the layers. This voltage is capable of driving a current through an external circuit and thereby producing useful work. When silicon is doped p-type with region of n-type doped silicon, holes from p-type side diffuse to n-type side and the electrons diffuse to p-type side.[1]

This creates an electric field. This electric field makes it easy for current to flow in one direction, but hard to flow in other. This electric field also separates electrons and holes and electric power can be extracted from the circuit.

Although practical solar cells have only been available since the mid 1950s, scientific investigation of the photovoltaic effect started in 1839, when the French scientist, Henri Becquerel discovered that an electric current could be produced by shining a light onto certain chemical solutions.

The effect was first observed in a solid material (in this case the metal Selenium [Se]) in 1877. This material was used for many years for light meters, which only required very small amounts of power. A deeper understanding of the scientific principles, provided by Einstein in 1905 and Schottky in 1930, was required before efficient solar cells could be made. A silicon solar cell which converted 6% of sunlight falling onto it into electricity was developed by Chapin, Pearson and Fuller in 1954, and this kind of cell was used in specialised applications such as orbiting space satellites in 1958. [2]

Today's commercially available silicon solar cells have efficiencies of about 18% of the sunlight falling on to them into electricity, at a fraction of the price of thirty years ago. There are now a variety of methods for the practical production of silicon solar cells (amorphous, single crystal, polycrystalline), as well as solar cells are made from other materials (e.g. copper indium diselenide, cadmium telluride, etc).

The development of solar cell use in Australia has been stimulated by:

a) The need for low maintenance, long lasting sources of electricity suitable for places remote from both the main electricity grid and from people, e.g. satellites, remote site water pumping, outback telecommunications stations and lighthouses.

b) The need for cost effective power supplies for people remote from the main electricity grid; e.g. Aboriginal settlements, outback sheep and cattle stations, and some home sites in grid connected areas.

c) The need for non-polluting and silent sources of electricity; e.g. tourist sites, caravans and campers.

d) The need for a convenient and flexible source of small amounts of power, e.g. calculators, watches, light meters and cameras.

e) The need for renewable and sustainable power, as a means of reducing global warming.

Together, these needs have produced a growing market for photovoltaic which has stimulated the innovation. As the market has grown, the cost of cells and systems has declined, and new applications have been discovered. [3]

Silicon solar cells are made using single crystal wafers, polycrystalline wafers or thin films.

Single crystal wafers are sliced, (approx. 1/3 to 1/2 of a millimetre thick), from a large single crystal ingot which has been grown at around 1400 C, which is a very expensive process. The silicon must be of a very high purity and have a near perfect crystal structure.


(a) (b) (c)

Figure 1.1 Different types of Silion solar cells [3]

(a) Single Crystal solar cells in panel

(b) Polycrystalline solar panel

(c) a-Si solar panel

Polycrystalline wafers are made by a casting process in which molten silicon is poured into a mould and allowed to set. Then it is sliced into wafers (Figure 1.1 - b). As polycrystalline wafers are made by casting, they are significantly cheaper to produce, but not as efficient as mono crystalline cells. The lower efficiency is due to imperfections in the crystal structure resulting from the casting process. [3]

Amorphous silicon, one of the thin film technologies, is made by depositing silicon onto a glass substrate from a reactive gas such as Silane ($SiH4$) (Figure 1.1 - c). Amorphous silicon is one of a number of thin film technologies. This type of solar cell can be applied as a film to low cost substrates such as glass or plastic. Other thin film technologies include thin multi crystalline silicon, copper indium diselenide/ cadmium sulphide cells, cadmium telluride/cadmium sulphide cells and gallium arsenide cells. There are many advantages of thin film cells including easier deposition and assembly, the ability to be deposited on inexpensive substrates or building materials, the ease of mass production, and the high suitability to large applications.

In solar cell production the silicon has dopant atoms introduced to create a p-type and an n-type region and thereby producing a p-n junction. This doping can be done by high temperature diffusion, where the wafers are placed in a furnace with the dopant introduced as a vapour. There are many other methods of doping silicon [3]. In the manufacture of some thin film devices, the introduction of dopants can occur during the deposition of the films or layers.

A silicon atom has 4 relatively weakly bound (valence) electrons, which bond to adjacent atoms. Replacing a silicon atom with an atom that has either 3 or 5 valence electrons will therefore produce either a space with no electron (a hole) or one spare electron that can move more freely than the others, this is the basis of doping. P-type doping, the creation of excess holes, is achieved by the incorporation into the silicon of atoms with 3 valence electrons, most often boron and n-type doping, the creation of extra electrons is achieved by incorporating an atom with 5 valence electrons, most often phosphorus (Figure 1.2).

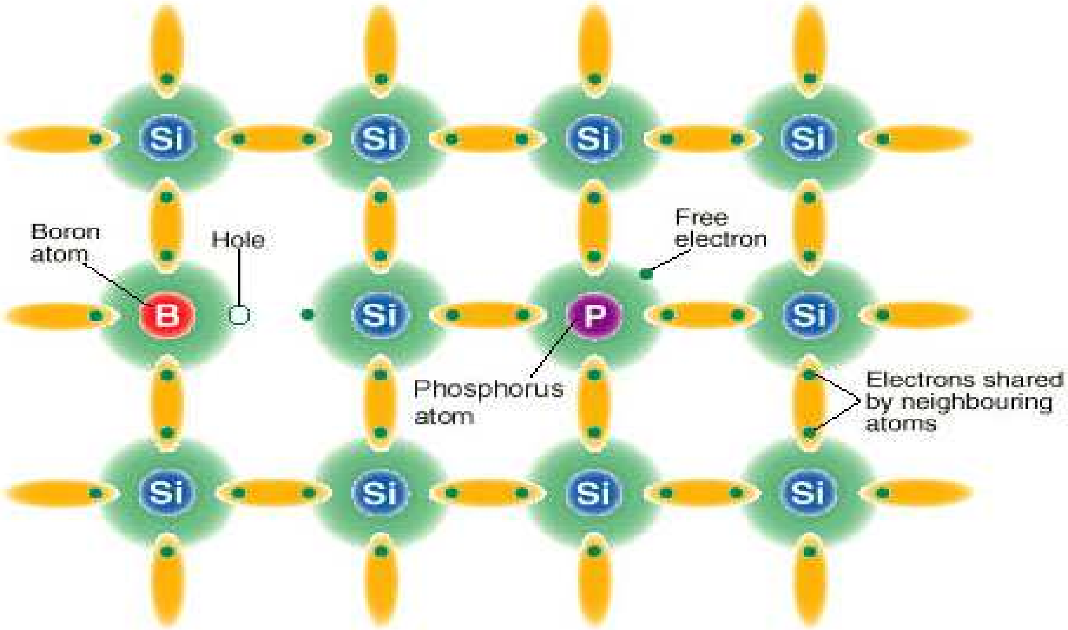


Figure 1.2 Silicon Crystal Lattice with Dopant Atoms [3]

Once a p-n junction is created, electrical contacts are made to the front and the back of the cell by evaporating or screen printing metal on to the wafer. The rear of the wafer can be completely covered by metal, but the front only has a grid pattern or thin lines of metal otherwise the metal would block out the sun from the silicon and there would not be any output from the incident photons of light.

To understand the operation of a PV cell, we need to consider both the nature of the material and the nature of sunlight. Solar cells consist of two types of materials, often p-type silicon and n-type silicon [4]. Light of certain wavelengths is able to ionise the atoms in the silicon and the internal field produced by the junction separates some of the positive charges ("holes") from the negative charges (“electrons”) within the photovoltaic device. The holes are swept into the positive or p-layer and the electrons are swept into the negative or n-layer. Although these opposite charges are attracted to each other, most of them can only recombine by passing through an external circuit outside the material because of the internal potential energy barrier.

Therefore if a circuit is made (Figure 1.3), power can be produced from the cells under illumination, since the free electrons have to pass through the load to recombine with the positive holes.

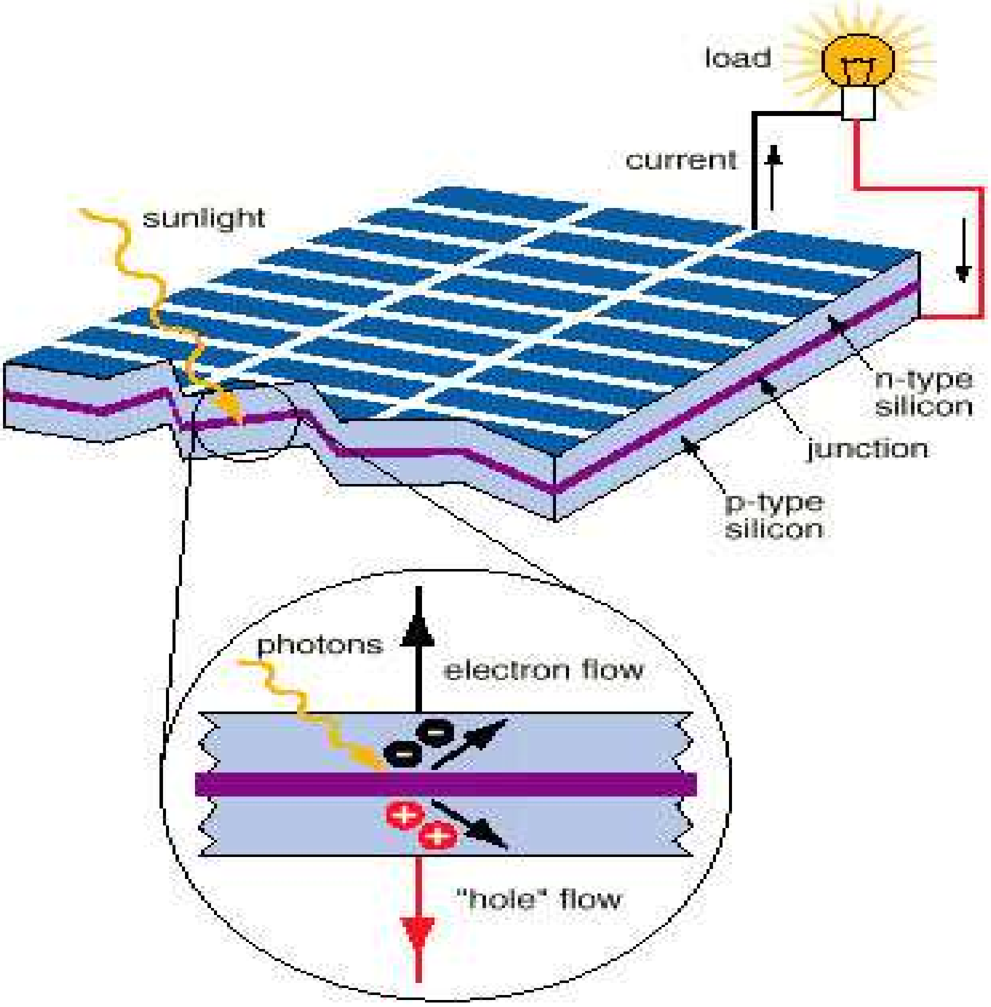


Figure 1.3 The Photovoltaic Effect in a Solar Cell [4]

The amount of power available from a PV device is determined by:

a) *The type and area of the material.*

b) The intensity of the sunlight.

c) The wavelength of the sunlight.

Single crystal silicon solar cells, for example cannot currently convert more than 25% of the solar energy into electricity, because the radiation in the infrared region of the electromagnetic spectrum does not have enough energy to separate the positive and negative charges in the material.

Polycrystalline silicon solar cells have an efficiency of less than 20% at this time and amorphous silicon cells, are presently about 10% efficient, due to higher internal energy losses than single crystal silicon. [4]

A typical single crystal silicon PV cell of 100 cm^2 will produce about 1.5 Watts of power at 0.5 Volts DC and 3 Amperes under full summer sunlight ($1000Wm^2$). The power output of the cell is almost directly proportional to the intensity of the sunlight. (For example, if the intensity of the sunlight is halved the power will also be halved).

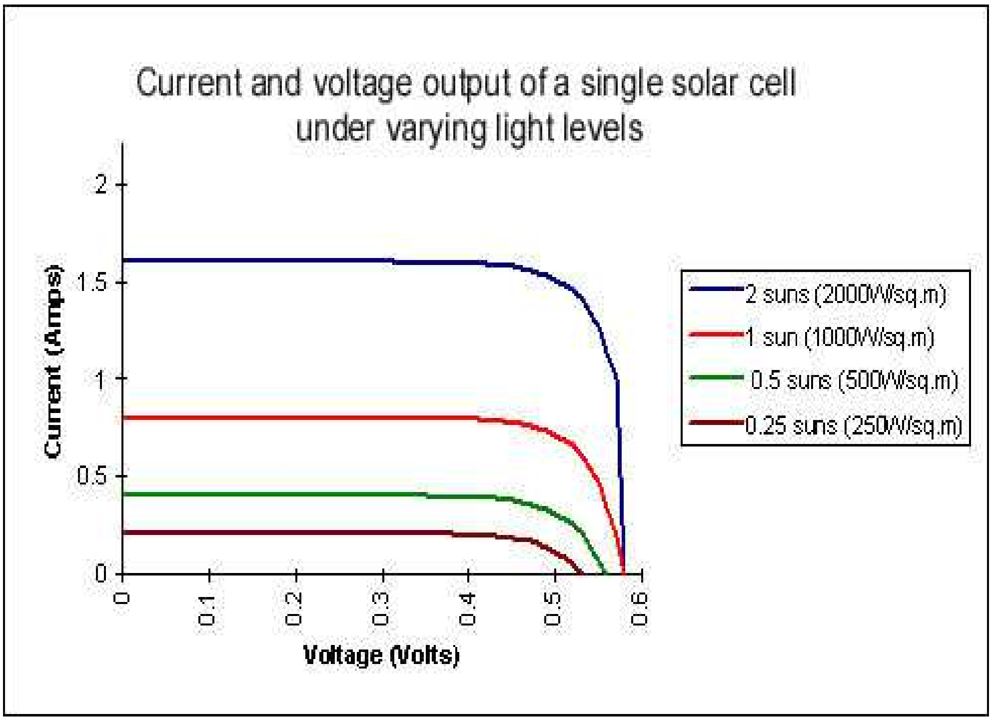


Figure 1.4 Graph showing current and voltage output of a solar cell at different light intensities [4]

An important feature of PV cells is that the voltage of the cell does not depend on its size, and remains fairly constant with changing light intensity. However, the current in a device is almost directly proportional to light intensity and size. When people want to compare different sized cells, they record the current density, or amps per square centimetre of cell area.

The power output of a solar cell can be increased quite effectively by using a tracking mechanism to keep the PV device directly facing the sun, or by concentrating the sunlight using lenses or mirrors [4]. However, there are limits to this process, due to the complexity of the mechanisms, and the need to cool the cells. The current output is relatively stable at higher temperatures, but the voltage is reduced, leading to a drop in power as the cell temperature is increased.

1.2 EFFECT OF SHUNT RESISTANCE (R_{SH}) AND SERIES RESISTANCE (R_S)

During operation, the efficiency of solar cells is reduced by the dissipation of power across internal resistances. These parasitic resistances can be modeled as a parallel shunt resistance (R_{SH}) and series resistance (R_S).

For an ideal cell, R_{SH} would be infinite and would not provide an alternate path for current to flow, while R_S would be zero, resulting in no further voltage drop before the load.

Decreasing R_{SH} and increasing R_s will decrease the fill factor (FF) and P_{MAX}. If R_{SH} is decreased too much, V_{OC} will drop, while increasing R_S excessively can cause I_{SC} to drop instead.

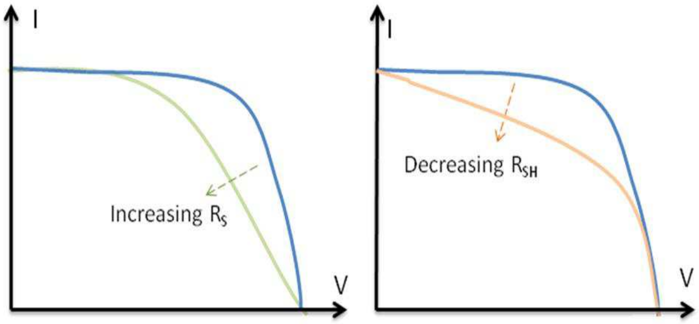


Figure 1.5 Effect of Diverging R_s & R_{SH} From Ideality [4]

It is possible to approximate the series and shunt resistances, R_S and R_{SH}, from the slopes of the I-V curve at V_{OC} and I_{SC}, respectively. The resistance at Voc, however, is at best proportional to the series resistance but it is larger than the series resistance. R_{SH} is represented by the slope at I_{SC}. Typically, the resistances at I_{SC} and at V_{OC} will be measured and noted.

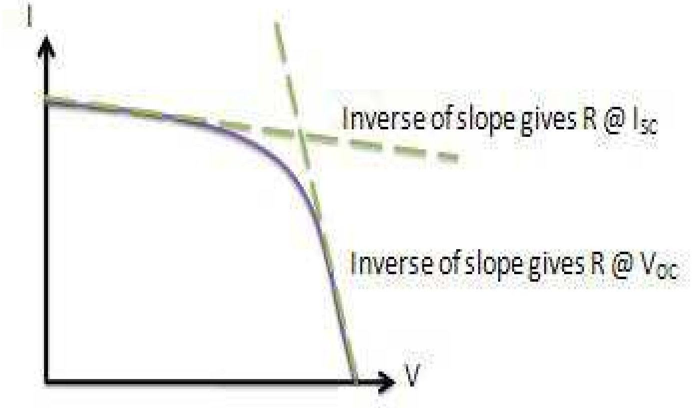


Figure 1.6 Obtaining Resistances from the I-V Curve [4]

If incident light is prevented from exciting the solar cell, the I-V curve shown in can be obtained as shown in Figure 1.7. This I-V curve is simply a reflection of the “No Light” curve from about the V-axis. The slope of the linear region of the curve in the third quadrant (reverse-bias) is a continuation of the linear region in the first quadrant, which is the same linear region used to calculate R_{SH}. It follows that R_{SH} can be derived from the I-V plot obtained with or without providing light excitation, even when power is sourced to the cell. It is important to note, however, that for real cells, these resistances are often a function of the light level, and can differ in value between the light and dark tests.

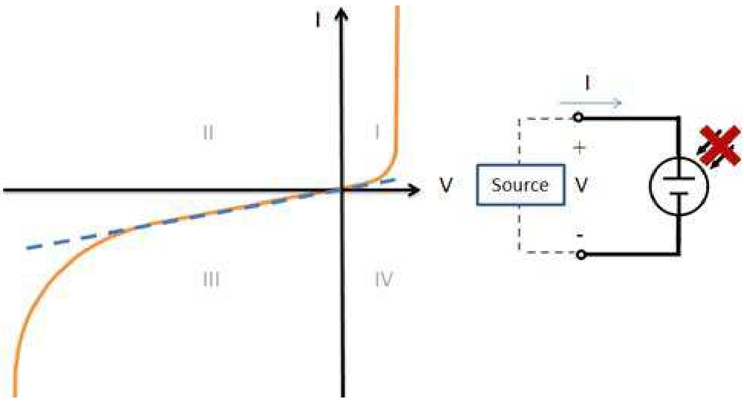


Figure 1.7 I-V characteristics of solar cell without light excitation [4]

The crystals used to make PV cells, like all semiconductors, are sensitive to temperature; depict the effect of temperature on an I-V curve as shown in Figure 1.8. When a PV cell is exposed to higher temperatures, I_{SC} increases slightly, while V_{OC} decreases more significantly.

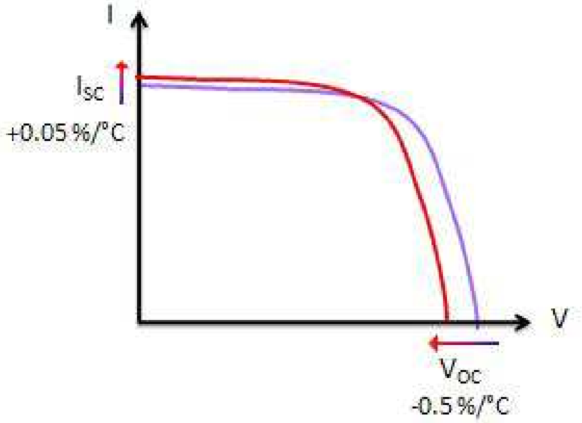


Figure 1.8 Temperature Effect on I-V Curve [4]

For a specified set of ambient conditions, higher temperature result in a decrease in the maximum power output P_{MAX}. Since the I-V curve will vary according to temperature, it is beneficial to record the conditions under which the I-V sweep was conducted. Temperature can be measured using sensors such as RTDs, thermistors or thermocouples.

1.3 HIGH PERFORMACE SOLAR CELL DESIGN

1.3.1 SILICON SOLAR CELL

A silicon **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. The term "photovoltaic" comes from the Greek word *photo* meaning "light", and from "Volt", the unit of electro-motive force, the volt, which in turn comes from the last name of the Italian physicist Alessandro Volta, inventor of the battery (electrochemical cell). The term "photo-voltaic" has been in use in English since 1849. [5]

The operation of a photovoltaic (PV) cell requires 3 basic attributes:

1. *The absorption of light, generating either electron-hole pairs or excitons.*
2. *The separation of charge carriers of opposite types.*
3. *The separate extraction of those carriers to an external circuit*

By far, the most prevalent *bulk* material for solar cells is crystalline silicon (abbreviated as a group as *c-Si*), also known as "solar grade silicon". Bulk silicon is separated into multiple categories according to crystallinity and crystal size in the resulting ingot, ribbon, or wafer. [5]

1. *Mono crystalline silicon* (c-Si): often made using the *Czochralski* process. Single-crystal wafer cells tend to be expensive, and because they are cut from cylindrical ingots, do not completely cover a square solar cell module without a substantial waste of refined silicon. Hence most *c-Si* panels have uncovered gaps at the four corners of the cells.

2. *Polycrystalline silicon*, or *multi crystalline silicon*, (poly-Si or mc-Si): made from cast square ingots — large blocks of molten silicon carefully cooled and solidified. Poly-Si cells are less expensive to produce than single crystal silicon cells, but are less efficient. United States Department of Energy data show that there were a higher number of polycrystalline sales than mono crystalline silicon sales.

3. *Ribbon silicon* is a type of polycrystalline silicon. It is formed by drawing flat thin films from molten silicon and results in a polycrystalline structure. These cells have lower efficiencies than poly-Si, but save on production costs due to a great reduction in silicon waste, as this approach does not require sawing from ingots.

4. *Mono-like-multi silicon*: Developed in the 2000s and introduced commercially around 2009, mono-like-multi, or cast-mono, uses existing polycrystalline casting chambers with small "seeds" of mono material. The result is a bulk mono-like material with poly around the outsides.

The solar cell works in three steps: [5]

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 as shown in Figure 1.9.

3. An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity.

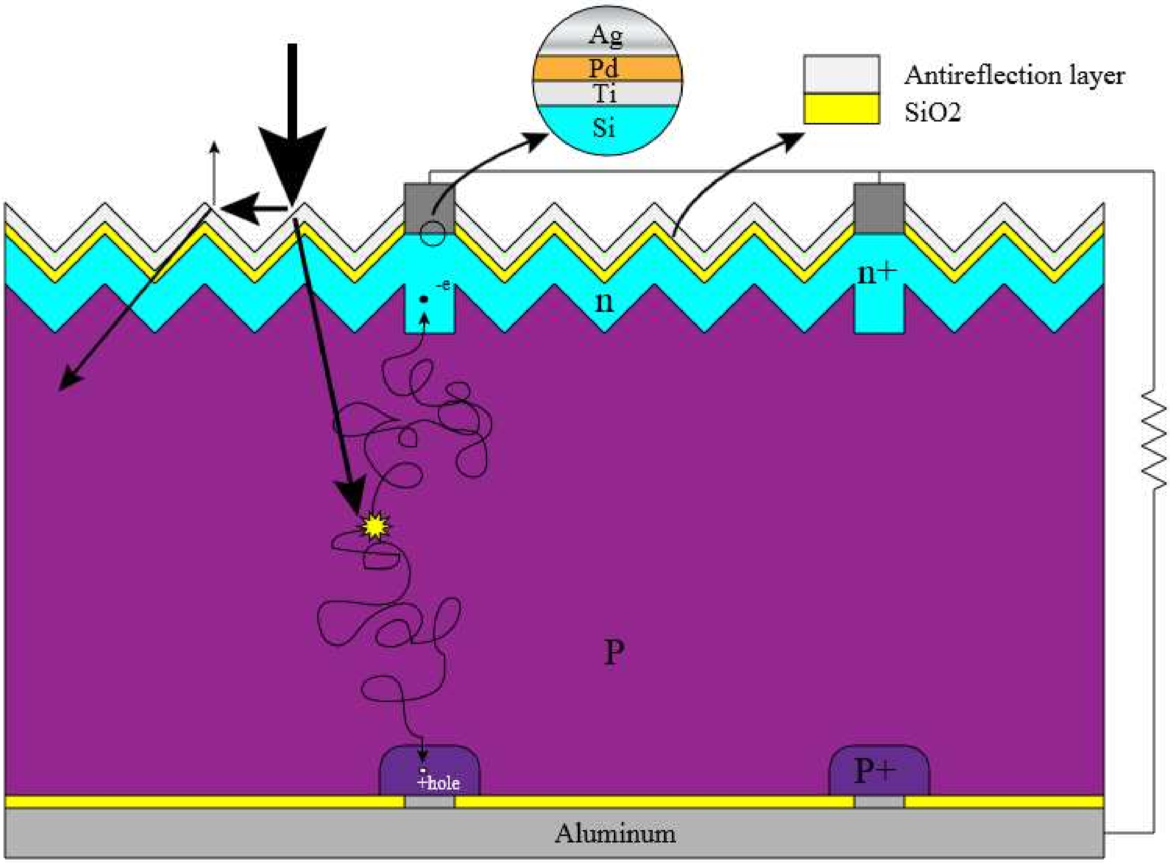


Figure 1.9 – Basic Silicon Solar Cell [5]

1.3.2 THIN FILM PLASMONIC SOLAR CELL

Thin film solar cells have the potential to significantly decrease the cost of photovoltaic. It, however, becomes a critical problem to trap the light in the solar cell to increase light absorption, i.e. to increase the conversion efficiency. To increase the conversion efficiency, nano-sized structures, such as textured surface and nano-particle deposition on the surface, have been proposed [6].

In this example, we consider an n/p crystalline silicon thin-film solar cell on which nano-sized metal particles, silver and gold, are distributed as shown in Figure 1.10, and explained how to simulate the light absorption using FDTD (Finite Difference Time Domain) Solutions. Simulation results show that, using the silver particle solar cell, we can get nearly 20% higher conversion efficiency compared with a bare solar cell.

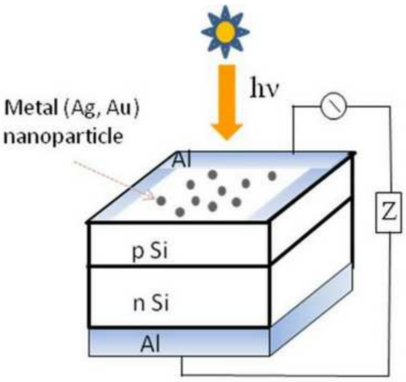


Figure 1.10 Thin Film Solar Cell [6]

Efficiency of single crystal Si cells (Laboratory) has been rising steadily to ~ 25% as a result of better understanding of the junction properties and innovations in cell design and fabrication technologies. Efficiency gap between best laboratory cells, sub modules/modules, and mass produced modules varies with the maturity of technology and can be at least 10% lower at every step so that the manufactured cell may be as low as 50% of the efficiency of the best laboratory cell. The world PV production of ~ 7900 MW in FY 2009 is primarily (~ 93%) based on single, crystal and polycrystalline silicon. With the existing technology and the material cost, the cost of Si cells can not be decreased significantly unless major innovations in the production of appropriate quality silicon thin sheets take place. Present day technology uses 8”or larger pseudo square of ~ 200μ m thickness, with an efficiency of ~ 15-16%. The energy payback period of such cells is ~ 3-4 years. The module life is about 25 years.

Specially designed silicon solar cells with efficiency ~ 18-20% are being manufactured on a limited scale for special applications (e.g. for concentration). Polycrystalline silicon solar cells with efficiency ~ 12-14% are being produced on large scale. Specially designed thin (~ 20 m) films silicon solar cells with efficiency ~ 12% have been fabricated on a lab scale. Production of hybrid thin film Si cells on MW scale is being pursued. [6]

ADVANTAGES OF THIN FILM SOLAR CELLS

Thin Film Solar Cells are required due to their following inherent advantages:

(a) Small thickness required due to high absorption, small diffusion length and high recombination velocity.

(b) Materials economy.

(c) Very low weight per unit power.

(d) Various simple and sophisticated deposition techniques of structures are available: amorphous, polycrystalline, epitaxial topography.

(e) Tailor ability of various optoelectronic properties e.g. Energy gap, electron affinity, work function, graded gap, etc.

One of the simplest solar cell designs is to produce with simple chemical conversion technique. Highest efficiency obtained ~10 %. Large scale production of modules with ~5% efficiency demonstrated during 70’s. Conversion remained an issue. Due to the emergence of higher efficiency Si.cells, this cell lost the battle of survival. Revival of this cell with suitable modifications is a possibility. [6]

The highest efficiency obtained in the lab cells is ~ 15%. Single junction cells degrade down to ~ 5-7% efficiency over a period dependent on how these are used. Numerous innovations such as cell integration, graded gap, multi-junctions, light trapping have contributed to the improvements in the cell performance. Stability has been improved with double and triple layer cells. Large MW plants for single and multiple junction cells have been set up. The best stabilized module efficiency is ~ 8%.

1.3.3 ORGANIC SOLAR CELL

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. [8]

The plastic used in organic solar cells has low production costs in high volumes. Combined with the flexibility of organic molecules organic solar cells are potentially cost-effective for photovoltaic applications. Molecular engineering (e.g. changing the length and functional group of polymers) can change the energy gap, which allows chemical change in these materials. The optical absorption coefficient of organic molecules is high, so a large amount of light can be absorbed with a small amount of materials. The main disadvantages associated with organic photovoltaic cells are low efficiency, low stability and low strength compared to inorganic photovoltaic cells.

Single layer organic photovoltaic cells are the simplest of the various forms of organic photovoltaic cells. These cells are made by sandwiching a layer of organic electronic materials between two metallic conductors, typically a layer of ITO with high work function and a layer of low work function metal such as Al, Mg or Ca. [8]

The difference of work function between the two conductors sets up an electric field in the organic layer. When the organic layer absorbs light, electrons will be excited to the LUMO and leave holes in the HOMO, thereby forming excitons. The potential created by the different work functions helps to separate the exciton pairs, pulling electrons to the positive electrode (an electrical conductor used to make contact with a non-metallic part of a circuit) and holes to the negative electrode. The current and voltage resulting from this process can be used to do work. Using electric fields is not the best way to break up excitons: heterojunction based cells which rely on effective fields are more effective.

Organic solar cells (OSCs) have various advantages compared with conventional Silicon based solar cells; for example, *low cost and flexibility*. However, it is necessary to improve the low conversion efficiency for many practical applications. There have been a number of recent studies to improve the conversion efficiency by increasing the light absorption with the help of nano-sized structures.

Organic solar cells are made of thin layers of organic materials with thickness in the 100 nano-meter range. They were first introduced by the research group of Dr. Ching Tang at Kodak Research Laboratories in 1986. The motivation for using organic dyes is to replace the expensive silicon in conventional photovoltaic cells and to apply simple production techniques. Additionally, organic solar cells can be prepared on plastic foil and so they are ideal candidates for flexible and portable systems. Today three different types of organic solar cells are known: the organic semiconducting material can either be comprised of so-called small molecules (SM solar cells) or polymers (polymer solar cells). The third type of organic solar cells is called dye-sensitised solar cell and contains a highly porous layer of titanium dioxide as electron transport layer on which dye molecules are adsorbed. Small molecule solar cells are processed in vacuum by physical vapour deposition; whereas polymer solar cells are processed by spin-coating or ink-jet printing (vacuum deposition is still necessary for metal deposition). Gratzel cells are typically processed by screen-printing of the titanium dioxide with subsequent sintering and dying. The OSOL group at the IAPP concentrates on small molecule solar cells. [8]

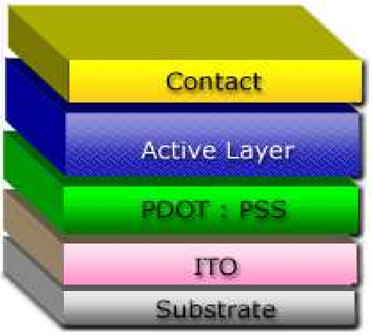


Figure 1.11 Structure of Organic Solar Cell [8]

1.4 PHOTONIC CRYSTAL BASED SOLAR CELL

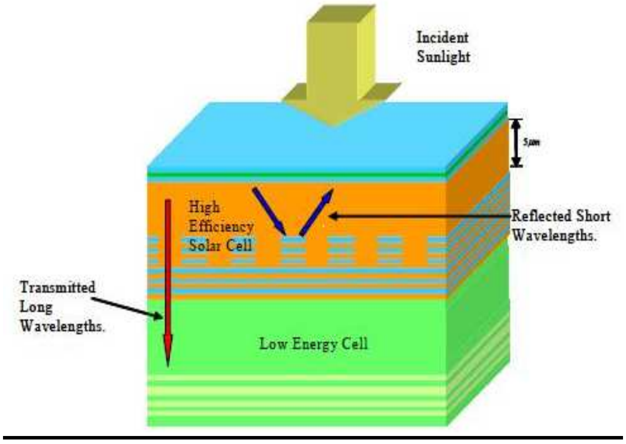


Figure 1.12 Schematic diagram showing a multiple junction solar cell with the short wavelengths being reflected back into the first cell and long wavelengths being transmitted to the lower energy solar cells [4]

A photonic crystal is a periodic arrangement of dielectric or metallic material with a lattice constant comparable to the wavelength of an electromagnetic wave. In the construction of the 1D-PhC, alternating layers of material with different refractive indices are stacked to form a structure that is periodic along one direction. The parameters that determine the band structure are the refractive index contrast and thicknesses of the constituting layers. A distributed-Bragg reflector is a good example of a 1D-Phc. [4]

1.4.1 INTRODUCTION TO PHOTONIC CRYSTAL

Photonic crystal is one of the most promising platforms for optical information processing as it can enable compact and efficient photonic devices and also their large scale integration on-chip. These are structures with periodic dielectric modulation on the order of the wavelength of light. Because of this periodicity, their study is analogous to the study of semiconductors in solid-state physics. The periodicity of the electronic potential in semiconductors, which is due to the regular arrangement of atoms in a lattice, gives rise to the electronic band-gap, which is forbidden energy bands for electrons. Similarly, the periodicity of the refractive index (i.e., dielectric constant) gives rise to photonic band-gap, forbidden energy bands for photons. Depending on the dimensionality of such periodicity, different classes of photonic crystals can be defined. One-dimensional (1D) photonic crystals, which are also known as the Distributed Bragg Reflectors (DBR), have been known for a long time and have been used mostly as mirrors particularly in Vertical Cavity Surface Emitting Lasers (VCSELs). The periodicity of dielectric constant in more than one dimension has been recently suggested simultaneously by Yablonovitch and John. Photonic crystal fibers are currently the most practical use of 2D photonic crystals. Although, 3D photonic crystals can have a complete photonic band gap and can control the light propagation in all directions, their fabrication is still significantly challenging.

1.4.2 THE MULTILAYER FILM: A ONE-DIMENSIONAL PHOTONIC CRYSTAL

The simplest possible photonic crystal, shown in figure 1.13, consists of alternating layers of material with different dielectric constants: a multilayer film. This arrangement is not a new idea. Lord Rayleigh (1887) published one of the first analyses of the optical properties of multilayer films. As we will see, this type of photonic crystal can act as a mirror (a Bragg mirror) for light with a frequency within a specified range, and it can localize light modes if there are any defects in its structure [3]. These concepts are commonly used in dielectric mirrors and optical filters (as in, e.g., Hecht and Zajac, 1997). The traditional way to analyze this system, pioneered by Lord Rayleigh (1917), is to imagine that a plane wave propagates through the material and to consider the sum of the multiple reflections and refractions that occur at each interface. In this chapter, we will use a different approach, the analysis of band structures, that is easily generalized to the more complex two and three-dimensional photonic crystals. By applying symmetry arguments, we can describe the electromagnetic modes sustainable by the crystal. The material is periodic in the z direction, and homogeneous in the x-y plane. As we saw in the previous chapter, this allows us to classify the modes using k_, k-z, and n: the wave vector in the plane, the wave vector in the z direction, and the band number. The wave vectors specify how the mode transforms under translation operators, and the band number increases with frequency. We can write the modes in the Bloch form:

$$Hn,k_z,k_{11}(r) = e^{ik}{}_{11}{}^{.\rho}e^{ikz\ .z}\,u_{n,kz,k11}(z)\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

The function $\mathbf{u}(z)$ is periodic, with the property $\mathbf{u}(z) = \mathbf{u}(z + R)$ whenever R is an integral multiple of the spatial period a. Because the crystal has continuous translational symmetry in the x-y plane, the wave vector $\mathbf{k}\_$ can assume any value. However, the wave vector k-z can be restricted to a finite interval, the one-dimensional Brillouin zone, because the crystal has discrete translational symmetry in the direction. Using the prescriptions, if the primitive lattice vector is aˆ$\mathbf{z}$ then the primitive reciprocal lattice vector is $(2\pi/a)$ˆ$\mathbf{z}$ and the Brillouin zone is $-\pi/a < kz \leq \pi/a$.

THE MULTILAYER FILM

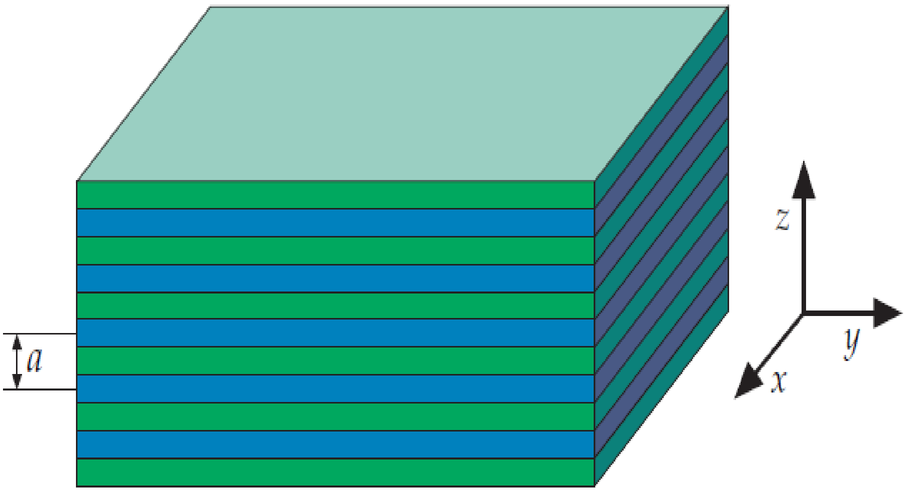


Figure 1.13 The multilayer film, a one-dimensional photonic crystal. The term "one dimensional" is used because the dielectric function $\varepsilon(z)$ varies along one direction (z) only. The system consists of alternating layers of materials (blue and green) with different dielectric constants, with a spatial period *a*. We imagine that each layer is uniform and extends to infinity along the *x* and *y* directions, and we imagine that the periodicity in the *z* direction also extends to infinity [3]

1.4.3 TWO-DIMENSIONAL BLOCH STATES

A two-dimensional photonic crystal is periodic along two of its axes and homogeneous along the third axis. A typical specimen, consisting of a square lattice of dielectric columns, Is shown in We imagine the columns to be infinitely tall; the case of a *finite* extent in the third direction is treated. For certain values of the column spacing, this crystal can have a photonic band gap in the *xy* plane. Inside this gap, no extended states are permitted, and incident light is reflected. Unlike the multilayer film, this two-dimensional photonic crystal can prevent light from propagating in *any* direction within the plane [3]. As always, we can use the symmetries of the crystal to characterize its electromagnetic modes. Because the system is homogeneous in the *z* direction, we know that the modes must be oscillatory in that direction, with no restrictions on the wave vector *k-z*. In addition, the system has discrete translational symmetry in the *x*-*y* plane. Specifically, $\varepsilon(\mathbf{r}) = \varepsilon(\mathbf{r}+ \mathbf{R})$, as long as **R** is any linear combination of the primitive lattice vectors *a*ˆ**x** and *a* ˆ**y**. By applying Bloch's theorem, we can focus our attention on the values of **k_** that are in the Brillouin zone. As before, we use the label *n* (band number) to label the modes in order of increasing frequency.

TWO-DIMENSIONAL PHOTONIC CRYSTALS

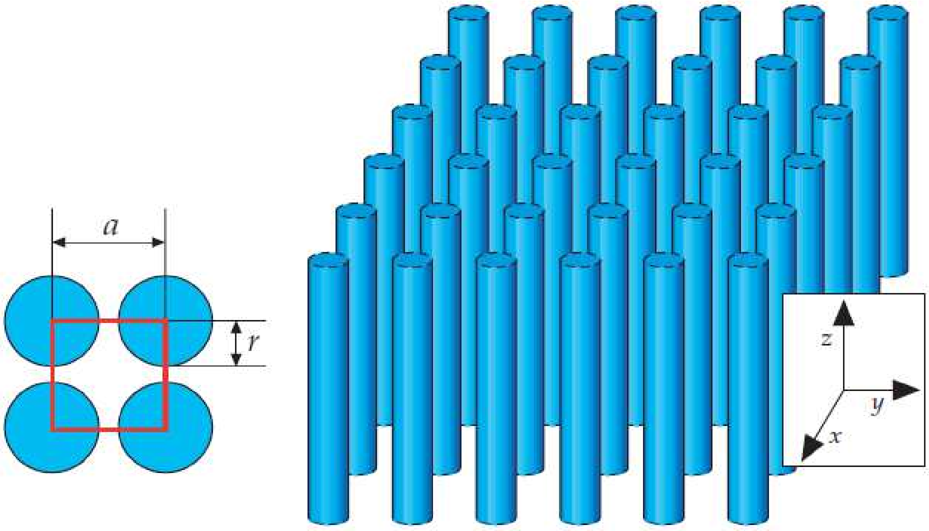


Figure 1.14 A two-dimensional photonic crystal. This material is a square lattice of dielectric columns, with radius *r* and dielectric constant *ε*. The material is homogeneous along the *z* direction (we imagine the cylinders are very tall), and periodic along *x* and *y* with lattice constant *a*. The left inset shows the square lattice from above, with the unit cell framed in red [3]

Indexing the modes of the crystal by *kz*, **k_**, and *n*, they take the now-familiar form of Bloch states

$$H(n,k_z,k_{11)}(r) = e^{ik}{}_{11}{}^{.\rho}e^{ikz\ .z}\,u_{n,kz,k11}(\rho)\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

In this equation, ***ρ*** is the projection of **r** in the *x*-*y* plane and **u**(***ρ***) is a periodic function, **u**(***ρ***) = **u**(***ρ*** + **R**), for all lattice vectors **R**. The modes of this system look similar to those of the multilayer film .The key difference is that in the present case, **k_** is restricted to the Brillouin zone and *k-z* is unrestricted. In the multilayer film, the roles of these two wave vectors were reversed. Also, **u** is now periodic in the plane, and not in the z direction as before. Any modes with k-$z = 0$ (i.e. that propagate strictly parallel to the xy plane) are invariant under reflections through the xy plane. This mirror symmetry allows us to classify the modes by separating them into two distinct polarizations. Transverse-electric (TE) modes have **H** normal to the plane, $\mathbf{H} = H(\boldsymbol{\rho})\hat{\mathbf{z}}$, and **E** in the plane, $\mathbf{E}(\boldsymbol{\rho}) \cdot \hat{\mathbf{z}} = 0$. Transverse-magnetic (TM) modes have just the reverse: $\mathbf{E} = E(\boldsymbol{\rho})\hat{\mathbf{z}}$ and $\mathbf{H}(\boldsymbol{\rho}) \cdot \hat{\mathbf{z}} = 0$. The band structures for TE and TM modes can be completely different. It is possible, for example, that there are photonic band gaps for one polarization but not for the other polarization. In the coming sections, we will investigate the TE and TM band structures for two different two-dimensional photonic crystals, mainly restricting ourselves to in-plane (k-$z = 0$) propagation. The results will provide some useful insights into the appearance of band gaps. [3]

1.4.4 THREE-DIMENSIONAL LATTICES

Although there are an infinite number of possible geometries for a three-dimensional photonic crystal, we are especially interested in those geometries that promote the existence of photonic band gaps. The results of the previous chapter suggest that we try structures that contain connected networks of dielectric channels. More precisely, the two-dimensional crystal with a complete band gap had dielectric “veins” for the TE polarization (in the plane) and dielectric spots for the TM polarization (out of the plane). However, the spots were actually long channels running in the z direction, parallel to the TM field. So, more generally, we want a network of dielectric channels running along all the directions in which the electric field can point. In three dimensions, then, we might try creating our crystals with arrays of tubes and spheres, analogous to the veins to the bonds and atoms of crystalline atomic lattices. It turns out that the choice of the lattice and how it is connected is critical in determining how easily we obtain a band gap. We will investigate several possibilities. Figure 1.15 is a schematic representation of several three-dimensional lattices of spheres in a cubic cell. The simplest lattice is formed by the blue spheres at the corners of the cube, with primitive lattice vectors $a\hat{x}$, $a\,\hat{y}$, and $a\hat{z}$. This is the simple cubic lattice. If we add the dark red spheres at the centers of the faces, we obtain a face-centered cubic (or fcc) lattice. The FCC lattice vectors are $(\hat{x} + \hat{y})a/2$, $(\hat{y} + \hat{z})\,a/2$, and $(\hat{x} + \hat{z})a/2$. For the FCC lattice, the smallest repeating unit (the primitive cell) is not the cubic cell shown in figure 1.15.

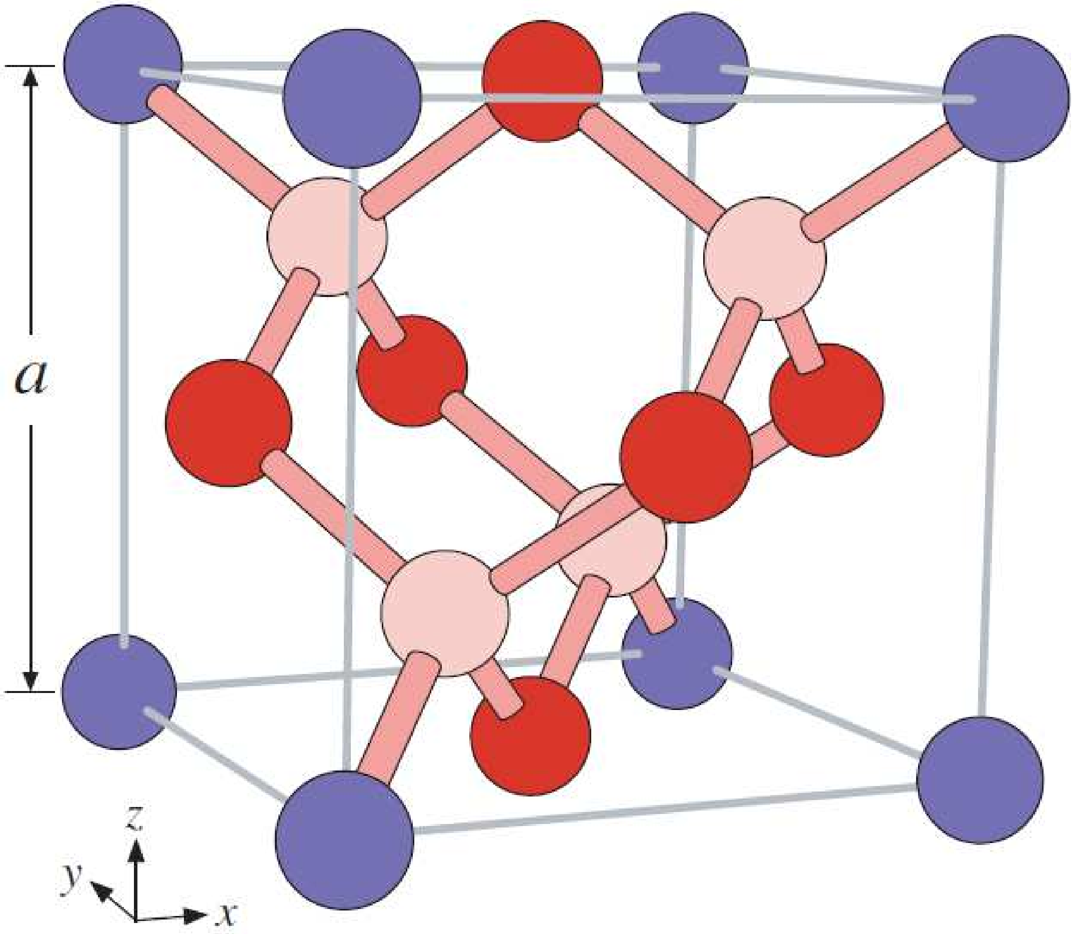


Figure 1.15 Ball-and-stick ("atomic") representation of several three-dimensional lattices in a cubic supercell, with a lattice constant *a*. The blue balls alone form a simple cubic lattice. Adding the dark red balls produces a face-centered cubic (fcc) lattice. Adding the pink balls as well produces a diamond lattice, with stick "bonds" (four bonds per ball) [3]

Rather, the primitive cell is a rhombo-hedron (with volume *a*3/4) whose edges are the three lattice vectors. The cubic cell contains four copies of this primitive cell, and is an example of a super cell. Finally, if we add the pink spheres, which represent another FCC lattice that is shifted by (*a*/4, *a*/4, *a*/4) relative to the blue spheres, then we obtain a diamond lattice. The periodicity in this case is the same as for the FCC lattice, but there are two "atoms" per rhombo-hedral primitive cell. In an atomic diamond lattice, the spheres would be carbon atoms, with each atom bonding to its four nearest neighbors, as illustrated in the figure. Returning to the dielectric case, we imagine these bonds to be dielectric veins. They provide the diamond lattice with the requisite channels along which the electric field lines can run. In fact, we shall see that all known photonic crystals with large band gaps (15% or larger with a dielectric contrast of 13 to 1) are closely related to the diamond structure. Consider a photonic crystal composed of only two different substances. We will examine two basic topologies, differing in whether the “atoms” and “bonds” are composed of the higher-_ material, or the lower-_ material. It is the *ratio* of the two dielectric constants that matters most, not the individual values. Scaling the entire dielectric function by some constant factor, $\varepsilon(\mathbf{r}) \rightarrow \varepsilon(\mathbf{r})/s2$, results in a trivial rescaling of the band structure, $\omega \rightarrow s\omega$. We define the dielectric contrast as the ratio of the dielectric constants of the high-ε and low-ε materials: ε high/ε low. As we have seen in earlier chapters, band gaps tend to appear in structures with a high dielectric contrast. The more significant the scattering of light, the more likely a gap will open up. One might wonder whether *any* dielectric lattice has a photonic band gap for a sufficiently high dielectric contrast. This is in fact the case for most two-dimensional crystals, at least for one polarization. For three-dimensional crystals, complete photonic band gaps are rarer. The gap must smother the entire three-dimensional Brillouin zone, not just any one plane or line. In most of the theoretical studies of these structures undertaken to date, the results are as follows. For a given crystal lattice, there is no photonic band gap until the dielectric contrast is increased to some threshold value. Above this nonzero threshold, the gap opens up and its width usually increases monotonically with the dielectric contrast, assuming optimal parameters are chosen. These optimal structural parameters (e.g., the radius of the tubes or spheres), which maximize the width of the band gap, vary with the dielectric constant.

1.4.5 USE OF PHOTONIC CRYSTALS IN SOLAR CELL

Photonic crystals are band pass filters that reflect short light wavelengths (400 - 1100 nm) and transmit longer wavelengths (1100 - 1800 nm) at the interface between two adjacent cells.

In addition, Nano structured diffractive gratings that cut into the photonic crystal layers are incorporated to redirect incoming waves and hence increase the optical path length of light within the solar cells.

1.5 OUTLINE OF DISSERTATION

- In Chapter 1, the basic introduction of Solar cell including the origin of Solar Cell, basic construction of solar cell, materials used for its construction, working of Solar cell along with VI characteristics has been discussed. The main limitation of Solar Cell is its reduced efficiency i.e. output electrical power obtained per unit the incident optical power – approx. 5%). The basic issues regarding the high performance Solar cell design has been discussed. Following that, the various high performance Solar Cell structures along with the advantages and limitations of each structure have been discussed briefly.

- In Chapter 2, the OSC has been focussed upon. Introduction to Organic Solar Cell includes the materials used for the construction of OSC. The various types of OSc like Single Layer OPVC, Bi-Layer OPVC and bulk hetero-junction OPVC has been discussed. Next the advantages of OSC over the conventional Solar Cell have been discussed. The applications and the uses of OSC have been also elaborated. Last the various issues related to the OSC design have been discussed.

- In Chapter 3, the basic literature review has been elaborated i.e. the recent work that has been carried out on increasing the efficiency of Solar Cell has been discussed.

- In Chapter 4, the designed Organic Solar Cell has been discussed. The simulation procedure and the results has been discussed which clearly depicts that absorption of the trapped light as a leaky mode of the PC waveguide structure has been enhanced and the location and magnitude of optical absorption varies strongly with wavelength on account of strong frequency dependence of photonic crystal structure.

- Chapter 5 has been focussed upon the conclusion from the results obtained from the designed structure and its future scope.

CHAPTER 2

ORGANIC SOLAR CELL

2.1 INTRODUCTION TO ORGANIC PHOTOVOLTAIC CELL (OPVC)

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. [13]

The plastic used in organic solar cells has low production costs in high volumes. Combined with the flexibility of organic molecules, organic solar cells are potentially cost-effective for photovoltaic applications. Molecular engineering (e.g. changing the length and functional group of polymers) can change the energy gap, which allows chemical change in these materials. The optical absorption coefficient of organic molecules is high, so a large amount of light can be absorbed with a small amount of materials. The main disadvantages associated with organic photovoltaic cells are low efficiency, low stability and low strength compared to inorganic photovoltaic cells.

2.2 ORGANIC PHOTOVOLTAIC MATERIALS USED IN OSC DESIGN

A photovoltaic cell is a specialized semiconductor diode that converts visible light into direct current (DC) electricity. Some photovoltaic cells can also convert infrared (IR) or ultraviolet (UV) radiation into DC. A common characteristic of both the small molecules and polymers used in photovoltaic is that they all have large conjugated systems. A conjugated system is formed where carbon atoms covalently bond with alternating single and double bonds; in other words these are chemical reactions of hydrocarbons [13]. These hydrocarbons' electrons p_z orbitals delocalize and form a delocalized bonding π orbital with a π antibonding orbital. The delocalized π orbital is the HOMO, and the π orbital is the LUMO. The separation between HOMO and LUMO is considered the band gap of organic electronic materials. The band gap is typically in the range of 1 – 4 eV. When these materials absorb a photon, an excited state is created and confined to a molecule or a region of a polymer chain. The excited state can be regarded as an electron-hole pair bound together by electrostatic interactions, i.e. excitons. In photovoltaic cells, excitons are broken up into free electron-hole pairs by effective fields. The effective fields are set up by creating a heterojunction between two dissimilar materials [13]. Effective fields break up excitons by causing the electron to fall from the conduction band of the absorber to the conduction band of the acceptor molecule. It is necessary that the acceptor material has a conduction band edge that is lower than that of the absorber material.

2.3 TYPES OF OPVC JUNCTIONS

There are three types of OPVC junctions on the basis of which they are classified:

(a) Single layer Organic Photovoltaic Cell

(b) Bi-layer Organic Photovoltaic Cell

(c) Bulk Hetero-junction photovoltaic Cell

2.3.1 SINGLE LAYER ORGANIC PHOTOVOLTAIC CELL

Single layer organic photovoltaic cells are the simplest of the various forms of organic photovoltaic cells. These cells are made by sandwiching a layer of organic electronic materials between two metallic conductors, typically a layer of indium tin oxide (ITO) with high work function and a layer of low work function metal such as Al, Mg or Ca. The basic structure of such a cell is illustrated in Figure 2.1.

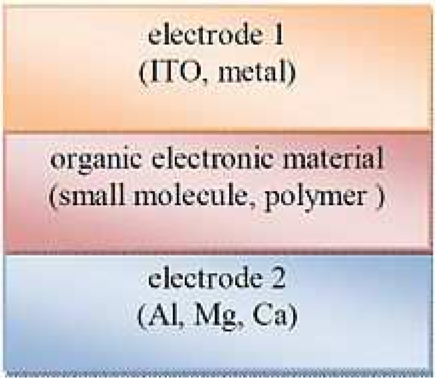


Figure 2.1 Sketch of a single layer organic photovoltaic cell [13]

The difference of work function between the two conductors sets up an electric field in the organic layer. When the organic layer absorbs light, electrons will be excited to the LUMO and leave holes in the HOMO, thereby forming excitons. The potential created by the different work functions helps to separate the exciton pairs, pulling electrons to the positive electrode (an electrical conductor used to make contact with a non-metallic part of a circuit) and holes to the negative electrode. The current and voltage resulting from this process can be used to do work. Using electric fields is not the best way to break up excitons: heterojunction based cells which rely on effective fields are more effective. [13]

In practice, single layer organic photovoltaic cells of this type do not work well. They have low quantum efficiencies (<1%) and low power conversion efficiencies (<0.1%). A major problem with them is that the electric field resulting from the difference between the two conductive electrodes is seldom sufficient to break up the photo generated excitons. Often the electrons recombine with the holes rather than reach the electrode. To deal with this problem, the multilayer organic photovoltaic cells were developed.

2.3.2 BI-LAYER ORGANIC PHOTOVOLTAIC CELL

This type of organic photovoltaic cell contains two different layers in between the conductive electrodes (Figure 2.2). These two layers of materials have differences in electron affinity and ionization energy, therefore electrostatic forces are generated at the interface between the two layers. The materials are chosen properly to make the differences large enough, so these local electric fields are strong, which may break up the excitons much more efficiently than the single layer photovoltaic cells do. The layer with higher electron affinity and ionization potential is the electron acceptor, and the other layer is the electron donor. This structure is also called a planar donor-acceptor hetero-junction. [17]

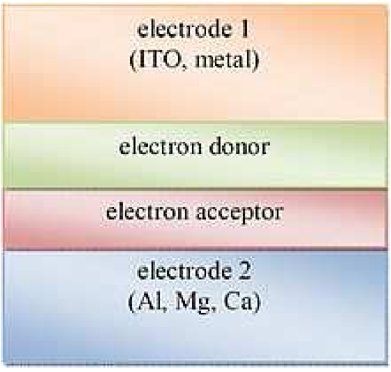


Figure 2.2 Sketch of a multilayer organic photovoltaic cell [17]

The diffusion length of excitons in organic electronic materials is typically on the order of 10 nm. In order for most excitons to diffuse to the interface of layers and break up into carriers, the layer thickness should also be in the same range as the diffusion length. However, a polymer layer typically needs a thickness of at least 100 nm to absorb enough light. At such a large thickness, only a small fraction of the excitons can reach the heterojunction interface. To address this problem, a new type of heterojunction photovoltaic cells is designed, which is the dispersed heterojunction photovoltaic cells. [17]

2.3.3 BULK HETERO-JUNCTION ORGANIC PHOTOVOLTAIC CELLS

In this type of photovoltaic cell, the electron donor and acceptor are mixed together, forming a polymer blend (Figure 2.3). If the length scale of the blend is similar to the exciton diffusion length, most of the excitons generated in either material may reach the interface, where excitons break efficiently. Electrons move to the acceptor domains then were carried through the device and collected by one electrode, and holes were pulled in the opposite direction and collected at the other side.

While most bulk heterojunction cells are of the two component variety, three component cells have also been explored. The third component, a secondary p-type donor polymer, acts to absorb light in a region of the solar spectrum different from that of the other donor. This in theory helps to maximize the amount of light absorbed by the cell [19]. These ternary cells can operate through one of three distinct mechanisms: charge transfer, energy transfer, or parallel-linkage. In charge transfer, both donors contribute directly to the generation of free charge carriers. Holes pass through only one donor domain before collection at the anode. In energy transfer, only one donor contributes to the production of holes. The second donor acts solely to absorb light, transferring extra photon energy to the first donor material. In parallel linkage, both donors produce excitons independently, which then migrate to their respective donor/acceptor interfaces and dissociate.

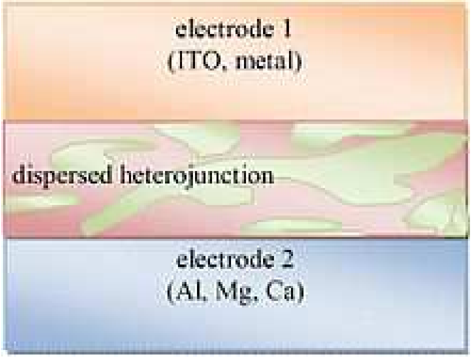


Figure 2.3 Sketch of a bulk junction photovoltaic cell [19]

2.4 BULK HETERO-JUNCTION ORGANIC SOLAR CELL WITH CONTROLLED GROWTH

Charge separation occurs at the donor acceptor interface. Whilst traveling to the electrode, a charge can become trapped and/or recombine in a disordered interpenetrating organic material, resulting in decreased device efficiency. Controlled growth of the heterojunction provides better control over positions of the donor-acceptor materials, resulting in much greater power efficiency (ratio of output power to input power) than that of planar and highly disoriented hetero-junctions (as shown in Figure 2.4). Thus, the choice of suitable processing parameters in order to better control the structure and film morphology is highly desirable. [17]

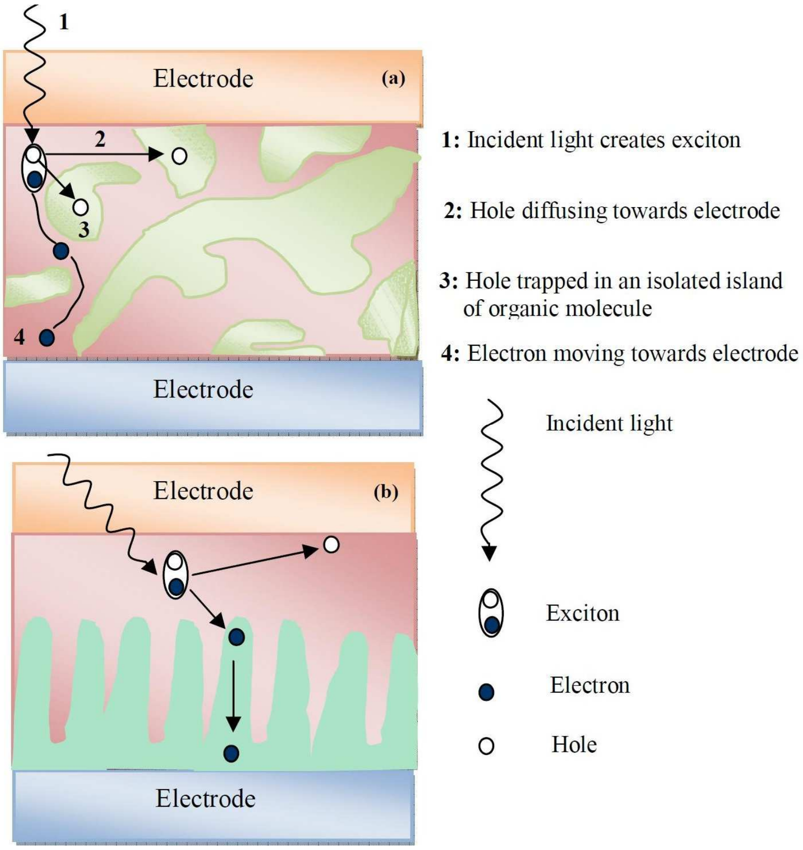


Figure 2.4 Highly folded hetero-junction with controlled growth [17]

2.5 WORKING OF ORGANIC SOLAR CELL

Operation of organic solar cells is mechanistically more complex. First, a molecule of an organic compound absorbs a photon and forms an excited state (exciton). Further, the exciton diffuses to a junction border between n- and p-types of semiconductor where it dissociates to form free charge carriers as shown in Figure 2.5. Organic p- and n-transporters are also known as donors and acceptors correspondingly.

If there is no junction border nearby, the exciton may recombine (decay) *via* photoluminescence, or thermally, back into the ground state of the molecule. This is the main reason, why mono- and bilayered (scheme above) organic solar cells were poorly performing devices until a new concept of bulk heterojunction has been introduced. Bulk heterojunction is a tight blend of a p-type conductor (donor), and n-type conductor (acceptor) in the photoactive layer of a device, where the concentration of each component often gradually increases when approaching to the corresponding electrode. This affords vast expansion of p-n-junction's total surface and strongly facilitates the excitons dissociation. The implication of this concept in practice allowed increase of power conversion efficiencies of up to 5% for all-organic solar cells.

In spite of the impressive results achieved with the realization of the bulk-heterojunction concept, the organic cells and materials still need to be strongly improved in order to find commercial application. Advantages of organic solar cells are: lightweight, environmentally friendly, no requirements for rare metals and minerals, no high temperatures and purity demand on the production stage, potentially inexpensive, virtually unlimited room for further material modification and improvement. [19]

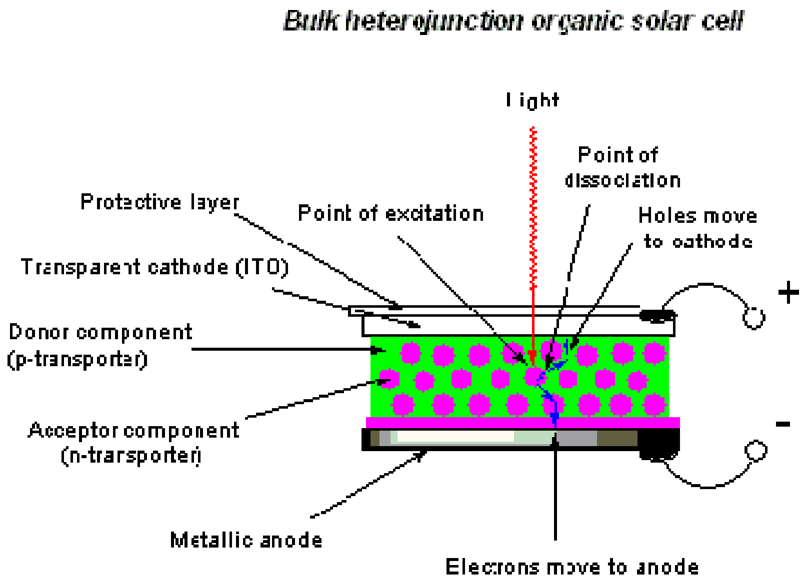


Figure 2.5 Bulk heterojunction organic solar cell [19]

2.6 ADVANTAGES OF ORGANIC SOLAR CELLS OVER CONVENTIONAL SOLAR CELLS

The advantages of OSC over conventional have been discussed below:

(a) Organic solar cells can be easily manufactured compared to silicon based cells, and this is due to the molecular nature of the materials used.

(b) Molecules are easier to work with and can be used with thin film substrates that are 1,000 times thinner than silicon cells (order of a few hundred nano-meters). This fact by itself can reduce the cost production significantly.

(c) Since organic materials are highly compatible with a wide range of substrates, they present versatility in their production methods. These methods include solution processes (inks or paints), high throughput printing techniques, roll-to-roll technology and many more, that enable organic solar cells to cover large thin film surfaces easily and cost-effectively. All above methods have low energy and temperature demands compared to conventional semi-conductive cells and can reduce cost by a factor of 10 or 20.

(d) An important advantage of organic materials used in solar cell manufacturing is the ability to tailor the molecule properties in order to fit the application. Molecular engineering can change the molecular mass, band gap, and ability to generate charges, by modifying e.g. the length and functional group of polymers. Moreover, new unique formulations can be developed with the combination of organic and inorganic molecules, making possible to print the organic solar cells in any desirable pattern or color.

(e) The tailoring of molecular properties and the versatility of production methods described on the previous page enable organic polymer solar cells to present a series of desirable properties. These solar modules are amazingly lighter and more flexible compared to their heavy and rigid counterparts, and thus less prone to damage and failure. They can exist in various portable forms (e.g. rolled form) and their flexibility makes storage, installation, and transport much easier.

(f) The energy consumed to manufacture a solar cell is less than the amount required for conventional inorganic cells. Consequently, the energy conversion efficiency doesn't have to be as high as the conventional cell's efficiency. An extensive use of organic solar cells could contribute to the increased use of solar power globally and make renewable energy sources friendlier to the average consumer. [19]

2.7 USES AND APPLICATIONS

The present situation indicates that organic solar cells cannot substitute for silicon cells in the energy conversion field. However their use seems to be more targeted towards specific applications such as:

- Recharging surfaces for laptops, phones, or to supply the power for small portable devices, such as cell phones and MP3 players.

- Other than the domestic use, recent developments have shown a military application potential for organic solar modules.

- Research in the US (Konarka) has shown that organic cells can be used in soldier tents to generate electricity and supply power to other military equipment such as night vision scopes and GPS (global positioning system) receivers. This technology is thought to be extremely valuable for demanding missions.

2.8 ISSUES RELATED TO ORGANIC SOLAR CELL DESIGN

Organic Solar cells have certain disadvantages including their low efficiency (only 5% efficiency compared to the 15% of silicon cells) and short lifetime. Nonetheless, their numerous benefits can justify the current international investment and research in developing new polymeric materials, new combinations, and structures to enhance efficiency and achieve low-cost and large-scale production within the next years. A commercially viable organic solar cell production is the target of the next decade.

CHAPTER 3

LITERATURE REVIEW

- **In 2013**, J. A. Rodriguez, M. Vetter presented the behaviour of the current density–voltage (J–V) characteristic curves of hydrogenated amorphous silicon (Si:H) tandem solar cells with heavy doped tunnelling junction of hydrogenated microcrystalline sili-con (μc–Si:H). The multi–junction solar cells were being used as an alternative to single junction (SJ) solar cells to reduce the Staebler–Wronski Effect (SWE) and to increase the solar cell stability and efficiency. The dual–junction (DJ) solar cell was formed by a stack of two p–i–n a–Si:H solar cells (top and bottom solar cells) whose J–V characteristic curves were also studied. Important in this kind of device was an exact adjustment of the current generation in top and bottom cells since both cells are connected in series and therefore must generate the same short circuit current density (Jsc). The J_{SC} could present miss–matching due to the different absorption of light in deeper parts of the device if the thickness of top and bottom cell were not well adjusted. Changing the relation between the thickness of the active layers of the tandem solar cell, the miss–matching in the Jsc value between top and bottom solar cells was minimized. The developed computer simulations of the electrical and optical properties of the tandem device helped to get a better understanding of tandem solar cells in order to design in a future work multi–junction solar cells made of different materials. [20]

- **In 2013,** Ruilong Yang, Zhizhong Bai, Dezhao Wang, and Deliang Wang fabricated a CdTe thin film solar cell with an absorber layer as thin as 0.5 μm. An efficiency of 7.9 % was obtained for a 1-μm-thick CdTe solar cell. The experimental results presented in study demonstrated that 1-μm-thick absorber layer is thick enough to fabricate CdTe solar cell with a decent efficiency. Formation of mono-grain CdS layer with grain size in submicron was fabricated. Heat treatment of a CdS precursor layer coated with a CdCl2 layer and under a high CdCl2 vapor pressure reduced oxide formation at the grain surface and promoted grain coalescence. High crystalline quality mono-grain CdS layer ensured homogenous intermixing of CdS and CdTe at the

CdS/CdTe interface. A saturated junction leakage current in the order of 10-10 A/cm2 and a short-circuit current as high as 25.1 cm/cm2 were obtained for a mono-grain-CdS/CdTe solar cell. The corresponding solar cell efficiency was 14.6%. [19]

- **In 2012,** Gang Li, Rui Zhu and Yang described about the polymer solar cell in such a way that the highly efficient and cost-effective polymer solar cells fabricated on textured fluorine doped transparent conductive electrodes are archived. Such electrodes with rough surface in combination with reflective back contacts provide efficient light-trapping by light scattering and multiple reflections to increase the path length of the light. Due to the increased light absorption in active layer, the resultant base on polymer fullerene system show 10% and 8% improvement in short current density and efficiency, respectively compared with the reference cell based on the flat electrodes. The maximum power conversion efficient of PSCs must rise above 15% in the laboratory corresponding to a module efficiency of around 10-12% before they can become practically useful. The unique properties of PSCs open the door for many novel applications. Stability is one of the major hurdles that must be tackled before PSCs can enter the market. Brabec et al. investigated the requirements that PSCs technology must meet for it to become competitive. [6]

- **In 2012,** Sajeev John described the designs of 3D that enhance the overall absorption of sunlight using architectures consisting of (equivalent bulk thickness) and no metallic mirrors. These crystals trap light through a parallel-to-interface negative refraction (PIR) effect that occurs over a broad angular and frequency range. These 3D photonic crystals exhibit an enhanced electromagnetic density of states, consisting of slow group velocity modes, in which the flow of energy is transverse to the depth of a thin film of material. In the case of a modulated nano wire photonic crystal solar cell, each wire contains a radial P-N junction and regions between the wires are filled with silica. This structure provides from 0 to 80 degrees. It is shown to absorb roughly 75% of all available sunlight in the wavelength range of 400-1000 nm. Power efficiencies in the range of 15-20% are shown using one micron of silicon. These nano structured photonic crystals offer additional opportunities for solar spectral reshaping and novel electronic management to rival and possibly surpass the well-known Shockley power efficiency limit. [33]

- **In 2011,** Ming Han Liao described about the high- efficient silicon nano-textured light – emitting diodes and solar cells with obvious photonic crystal effect that the light emission efficiency ion silicon light emitting diodes (LEDS) with nano-trench structure at the top surface could be enhanced about 10 times than the control planner device. The nano textured silicon solar cell are also observed and demonstrated to have higher open circuit voltage, short circuit current, electric transformation efficiency due to more light trapping, low reflection on nano textured surface and more carrier collected in larger n-p junction area. The photonic crystal effect in the characteristics of special wavelength extraction is also observed successfully in the high efficient solar cell. The solar cell efficiency can be improved about 2.9% from (12 - 14.9%) by design nano surface structure. The high efficiency about 14.9% of Si solar cell have been successfully achieved by the nano scale textured surface and optimal surface-clean process. The study proves that the modern multiple vertical junction solar cell with in the μm-scale structure are worthy of continuously scaling down to the nm-scale structure and then get to the further solar cell efficiency enhancement. The high-performance Si-based optical devices make them attractive at integrate Si optoelectronic devices into the Si chip for the future real application. [9]

- **In 2011**, Jinhui Yuan, Xinzhu Sang , proposed about Highly Efficient Anti-Stokes Signal Conversion by Pumping in the Normal and Anomalous Dispersion Regions in the Fundamental Mode of Photonic Crystal Fiber**.** By pumping near the zero dispersion wave length, the highly efficient anti-Stokes signal conversions of the femto second pulses in the fundamental mode of photonic crystal fiber with the zero dispersion wavelength of 848 nm have been achieved within the wavelength range of 644 to 543 nm. the corresponding conversion efficiency can be up to 33%, 39%, and 46%.In summary, based on the phase-matched FWM, the highly efficient anti-Stokes signal conversions in the fundamental mode of PCF have been achieved through pumping in the normal and anomalous dispersion regions. The reasons for difference between the experiment and the theory result are analyzed. [7]

- **In 2011,** E. Drouark, Y. Park, O. El Daif, X. Letartre, P. Viktorovitch, A. Fave, A. Kaminski, M. Lemiti, C. Seassal A proposed a design to significantly increase the absorption of a thin layer of absorbing material such as amorphous silicon. This was achieved by patterning a one-dimensional photonic crystal (1DPC) in that layer. Indeed, by coupling the incident light into slow Bloch modes of the 1DPC, they controlled the photon lifetime and then, enhanced the absorption integrated over the whole solar spectrum. Optimal parameters of the 1DPC maximize the integrated absorption in the wavelength range of interest, up to 45% in both S and P polarization states instead of 33% for the unpatterned, 100 nm thick amorphous silicon layer. Moreover, the absorption was tolerant with respect to fabrication errors, and remains relatively stable if the angle of incidence is changed. [29]

- **In 2010,** AC Varonides & RA Spalletta demonstrated a highly successful new solar cell design was pursued. They proposed a new high efficiency solar cell design, consisting of two cells in tandem: the top cell is a triple n" - n – p hetero junction and the bottom one was a p - i - n multi quantum well cell tuned at 1eV through appropriate (narrow-wide gap) hetero-layers. Both PV sub-units may stand (with individual collection efficiency values at 19.7 and 22.190/0 respectively) alone as individual solar cells, but in that case they contribute solar photon absorption from the visible to the infrared sector of the solar spectrum. Tuning at 1eV offers a chance for solar photon absorption at long wavelengths (especially at 1,240 nm), while small variation of quantum well widths generates optical gap variation in the neighbourhood near and above of the mentioned value. Absorption edge tuning was a reasonable selection for long wavelength absorption (at 1ev and beyond). Efficiency values above the 400/0 *threshold* seem to be feasible with improvements of that design. They concluded that for a suitable selection of well width values, most (if not all) of the long IR solar spectrum could be absorbed. [27]

- **In 2010,** Emmanuel Drouard, Guillaume Gomard, Xianqin Meng, Ounsi El Daif,, Anne Kaminski-Cachopo, Alain Fave, Mustapha Lemiti, Christian

Seassal demonstrated that the optical absorption of an ultra-thin active layer solar cell can be significantly increased by engineering properly both the in plane patterning of the active layer and the vertical stack. This structuration both controls incident light coupling into slow light modes of the photonic crystals and photon lifetime in the absorbing material. Numerical results on optical and electrical properties will be presented, as well as preliminary optical and electrical characterizations of silicon based demonstrators. [30]

- **In 2010,** James G. Mutitu, Shouyuan Shi, Allen Barnett, Dennis W. Prather presented a new angular selective filter design that was based on photonic band gap engineering principles. The operation of the filter was based on the occurrence of angular-dependent photonic stop bands and pass bands in a photonic crystal structure. Such a filter allows for the propagation of normally incident light while disallowing the propagation of obliquely incident light waves. When the filter was applied to a solar cell structure that consists of a diffraction grating structure on the back surface, a high-efficiency light trap can be formed. Hence, the light-trapping capacity of the new structure was dependent on the photonic band structure of the light filter rather than on refractive optical properties of the active photovoltaic material. The paper presents a model of such a structure and investigates the possibilities afforded by the new structure. [32]

- **In 2010,** M. H. Liao proposed about the Investigation of Optimal Si-Si Ge Hetero-Structure Thin-Film Solar Cell with Theoretical Calculation and Quantitative Analysis The characteristics of a SiGe hetero-structure solar cell such as short-circuit current density (*J*sc), open-circuit voltage (*V*oc), fill factor (FF), and efficiency with optimal Ge concentration are investigated in this paper. The average Ge concentration was systematically changed in the range from 0% to 30%.With the optimization of Ge concentration and clean process condition, the overall efficiency of a Si0.9Ge0.1 solar cell is found to be improved about 4% than that in the control Si solar cell. The optimal Ge concentration in the Si Ge-based solar cell has been investigated qualitatively by the systemic experiment and theoretical calculation. With the appropriate addition of Ge to a Si Ge-based solar cell, the short current density is successfully increased without affecting the open-circuit voltage and then the overall efficiency is successfully improved by about simmilar 4% than the controlled Si solar cell. [8]

- **In 2009,** Hari P. Paudel, Dillip Dachhepati, Umesh Gautam, Khadijeh Bayat and Mahdi Farrokh Baroughi based on the present up conversion efficiency of rare earth doped nano crystals estimated the necessary up conversion efficiency of luminescent materials to effectively enhance the efficiency of solar cells. Emission enhancement of luminescent material by surface plasmons resonance was investigated. The detail study on quenching of enhanced near-field of metallic photonic crystal by luminescent materials was performed by finite difference time domain simulation. [31]

- **In 2009**, Doo-Hyun Ko, John r. Tumleston explained about the photonic crystal geometry for organic solar cell in an enhanced way such that they presented one- (1D) and two-dimensional (2D) periodic nano structured designs for organic photo-voltaic where a photonic crystal is formed between blended poly-3-hexylthiophene-phenyl-C61-butyric acid methyl ester and nano crystalline zinc oxide. Absorption enhancements over the full absorption range of PCBM of 20% (one polarization) and 14% are shown for the 1D and 2D structures, accordingly used in the solar cell. These improvements result in part from band edge excitation in quasi-guided modes. In the summary of is still quite promising organic solar cells are still quite promising. A major advantage is obtained that their morphology are relatively easy to optimize. In such a way that flexibility, large area, light-weight, and the ability to self-repair are all attractions for research. The largest challenge remains in the low efficiency mainly due to poor charge mobility. [13]

- **In 2009,** Bryan Ellis, Tomas Sarmiento, James Harris, and Jelena Vuckovic concluded that the maximum theoretical efficiency of direct solar energy conversion by semiconductor solar cells was only achievable in cells where radiative recombination dominates. Radiative recombination sets an upper limit to the minority carrier lifetime and any non radiative processes decrease the conversion efficiency of the cell. GaAs is a good candidate material for achieving this efficiency limit because the internal quantum efficiency in high quality material can be greater than 99%. In order to reach the theoretical upper efficiency limit, most of this radiative recombination must be inhibited. This is because the derivation of the limiting efficiency assumes that the only spontaneous emission that escapes the cell is emitted within the solid angle subtended by the incident solar radiation. This limiting efficiency evaluated at the GaAs bandgap of 1.42eV is 38.7%. In practice, two sources of spontaneous emission reduce the efficiency of actual solar cells. First, because the solid angle subtended by the incident sunlight is small even when concentrated there will be extra spontaneous emission that is not emitted in the direction of the incident radiation. Second, because of the high refractive index of most semiconductors, most of the emission will be coupled to guided modes which may not be reabsorbed. Taking into account these two sources of spontaneous emission loss, and assuming that no emission is reabsorbed, the maximum conversion efficiency of a GaAs solar cell (one sun) is derived to be 26.8% close to the record GaAs solar cell efficiency of 25.1% . This observation suggested that there is extra spontaneous emission that reduces the efficiency of many high efficiency solar cells and that considerable efficiency gains can be realized by engineering the cells to reduce this emission.[34]

- **In 2009,** Emmanuel Drouard, Yeonsang Park, Ounsi EI Dair, Xavier Letartre, Pierre Viktorovitch, Alain Fave Anne Kaminski, Mustapha Lemitt, Christian Seassal concluded that the absorption of an ultra-thin layer can be significantly increased by patterning a photonic crystal. The incident light couples into slow. Bloch modes, enabling a robust control of the photon lifetime and then, the enhancement of the absorption integrated over the whole solar spectrum. [21]

- **In 2009,** D. Duché, JJ. Simon, L. Escoubas, Ph. Torchio, J. Le Rouzo, W. Vervisch, F. Flory gave the design of the active layer of organic solar cells in the shape of a photonic crystal. An optimised photonic crystal allowed trapping the light in a layer at specific wavelengths thanks to a coupling of a low group velocity mode called slow Bloch mode. This method was used to design two structures which allow to improve absorption of light in organic solar cells for wavelengths close to the band gap of an active layer composed of poly-3-hexylthiophène (P3HT) and [6,6]-phenyl-C61-butiryc acid methyl ester (PCBM). Nevertheless, while the first structure does not allow an efficient charges harvesting by the electrodes, the second structure can be beneficial for both the optical and the electrical properties of the cell thanks to the structuring of the Poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT:PSS) layer. [22]

- **In 2009,** E. Drouard, Y. Park, O. El Daif, X. Letartre proposed a design to significantly increase the absorption of a thin layer of absorbing material such as amorphous silicon. This was achieved by patterning a one-dimensional photonic crystal (1DPC) in this layer. Indeed, by coupling the incident light into slow. Bloch modes of the 1DPC, we can control the photon lifetime and then, enhance the absorption integrated over the whole solar spectrum. Optimal parameters of the 1DPC maximize the integrated absorption in the wavelength range of interest, up to 45% in both S and P polarization states instead of 33% for the un-patterned, 100 nm thick amorphous silicon layer. Moreover, the absorption is tolerant with respect to fabrication errors, and remains relatively stable if the angle of incidence is changed. [23]

- **In 2009,** James G. Mutitu, Shouyuan Shi Allen Barnett, Christiana Honsberg and DennisW. Prather presented novel light trapping designs applied to thin (5 micron) silicon solar cells. The design structures incorporated diffractive gratings to increase the optical path length of light within the solar cells. They incorporated a combination of dielectric and metallic materials to create the grating and formed a one dimensional photonic crystal stack with the dielectric materials to which then added the metallic layers. The combination of the two materials enhanced the reflective properties of the gratings and thus increasing their effectiveness in light trapping. They used the particle swarm optimization and scattering matrix methods to realize the design structures. [24]

- **In 2009**, Emmanuel Drouard, Yeonsang Park, explained about Photonic crystal silicon based structures for thin film solar cell A design is proposed to significantly increase the absorption of a thin layer of absorbing material such as amorphous silicon. This is achieved by patterning a one-dimensional photonic crystal (1DPC) in this layer. Indeed, by coupling the incident light into slow Bloch modes of the 1DPC, we can control the photon lifetime and then, enhance the absorption integrated over the whole solar spectrum. Optimal parameters of the 1DPC maximize the integrated absorption in the wavelength range of interest, up to 45% in both S and P polarization states instead of 33% for the unpatented, 100 nm thick amorphous silicon layer. The contribution of a PC structure using light modes coupled in the normal direction was demonstrated both theoretically and experimentally for a simple a-Si layer, and proposals were made for a complete solar cell structure, in combination with usual techniques as antireflection coatings and back reflector patterning. [15]

- **In 2009,** Xianqin Meng. Valerie Depauw, Guillaume Gomard, Ounsi EI Daif, Christos Trompoukis, Emmanuel Drouard, Alain Fave, Frederic Dross, Ivan Gordon and Christian Seassal presented the integration of an absorbing photonic crystal within a thin film photovoltaic solar cell. Optical simulations performed on a complete solar cell revealed that patterning the epitaxial crystalline silicon active layer as a ID and 2D photonic crystal enabled to increase its integrated absorption by 37%abs and 68%abs between 300 nm and 1100 nm, compared to a similar but unpatterned stack. In order to fabricate such promising cells, a specific fabrication processes based on holographic lithography, inductively coupled plasma etching and reactive ion etching has been developed and implemented to obtain ultrathin patterned solar cells. [25]

- **In 2009,** James G. Mutitu1, Shouyuan Shi, Allen Barnett, Christiana Honsberg and DennisW. Prather presented novel light trapping designs applied to thin (5 micron) silicon solar cells. The design structures incorporated diffractive gratings to increase the optical path length of light within the solar cells. They incorporated a combination of dielectric and metallic materials to create the gratings. They formed a one dimensional photonic crystal stack with the dielectric materials to which we then add the metallic layers. The combination of the two materials enhanced the reflective properties of the gratings and thus increased their effectiveness in light trapping. [28]

- **In 2010,** James G. Mutitu, Shouyuan Shi explained about Angular Selective Light Filter Based on Photonic Crystals for Photovoltaic Applications and presented a new angular selective filter design that is based on photonic band gap engineering principles. The operation of the filter is based on the occurrence of angular-dependent photonic stop bands and passes bands in a photonic crystal structure. The light-trapping capacity of the new structure is dependent on the photonic band structure of the light filter rather than on refractive optical properties of the active photovoltaic material. The SC EPhCM structure solves the fundamental problem of the out coupling of light that is obliquely incident on the front surface, of the solar cell, from within the active region. This out coupling of light is limited by the angular selectivity of the EPhCM structure, and hence, the absorption characteristics are greatly increased by up to a factor of 250 close to 1100 nm. [32]

- **In 2008,** Dengyuan Song, Jingfeng Xiong, Zhiyan Hu, Gaofei Li, Hongfang Wang, Haijiao An, Bo Yu, Brian Grenko, Kevin Borden, Kenneth Sauer, Thomas Roessler, Jianhua Cui, Haitao Wang, Jan Bultman, A.H A presented a novel high efficiency solar cell and module technology, named PANDA, using crystalline n-type CZ Si wafers has moved into large-scale production at Yingli. The first commercial sales of the PANDA modules commenced in mid 2010. Up to 600MW of mass production capacity from crystal-Si growth, wafer slicing, cell processing and module assembly have been implemented by the end of 2011. The PANDA technology was developed specifically for high efficiency and low cost. In contrast to the existing n-type Si solar cell manufacturing methods in mass production, this new technology is largely compatible with a traditional p-type Si solar cell production line by conventional diffusion, SiNx coating and screen-printing technology. With optimizing all technologies, Yingli's PANDA solar cells on semi-square 6-inch n-type CZ wafers (cell size 239cm2) have been improved to currently have an average efficiency on commercial production lines exceeding 19.0% and up to 20.0% in pilot production. [26]

CHAPTER 4

ORGANIC SOLAR CELL WITH PHOTONIC CRYSTAL STRUCTURE

4.1 INTRODUCTION

Organic solar cells (OSCs) have various advantages compared with conventional Silicon based solar cells; for example, low cost and flexibility. However, it is necessary to improve the low conversion efficiency for many practical applications. There have been a number of recent studies to improve the conversion efficiency by increasing the light absorption with the help of nano-sized structures. One method is to use photonic crystal (PC) structures in the photoactive layer where the light absorption can be enhanced by trapping light as leaky modes within the PC structures. In this section, we show how to simulate the light absorption within the OSC with PC (PCOSC) using FDTD Solutions.

OSC structure has bulk hetero-junction blend with poly-3-hexylthiophene/[6,6]-phenyl-C61-butyric acid methyl ester (P3HT:PCBM) used as a photoactive layer. The OSC has a PC structure formed by the bulk hetero-junction blend and nc-ZnO as shown in Figure 4.1. Due to the existence of waveguide anomalies caused by a resonant interaction of incoming light with a leaky (or a quasi-guided) mode of the PC waveguide, the light absorption can be enhanced compared with conventional flat solar cells.

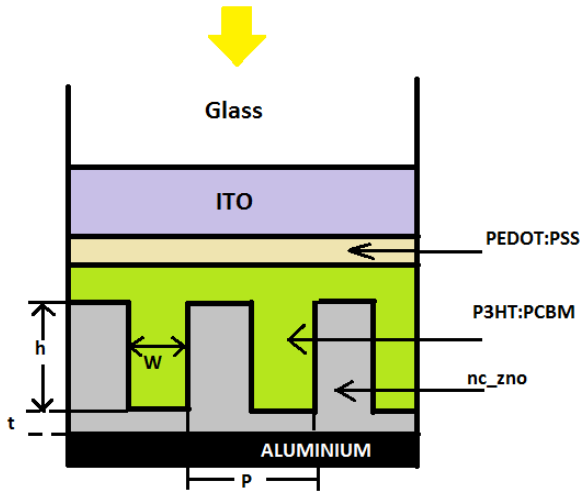


Figure 4.1 Organic solar cell with photonic crystal structure

4.2 SIMULATION SETUP

Here it is summarized how to set up simulations for PCOSC using FDTD Solutions.

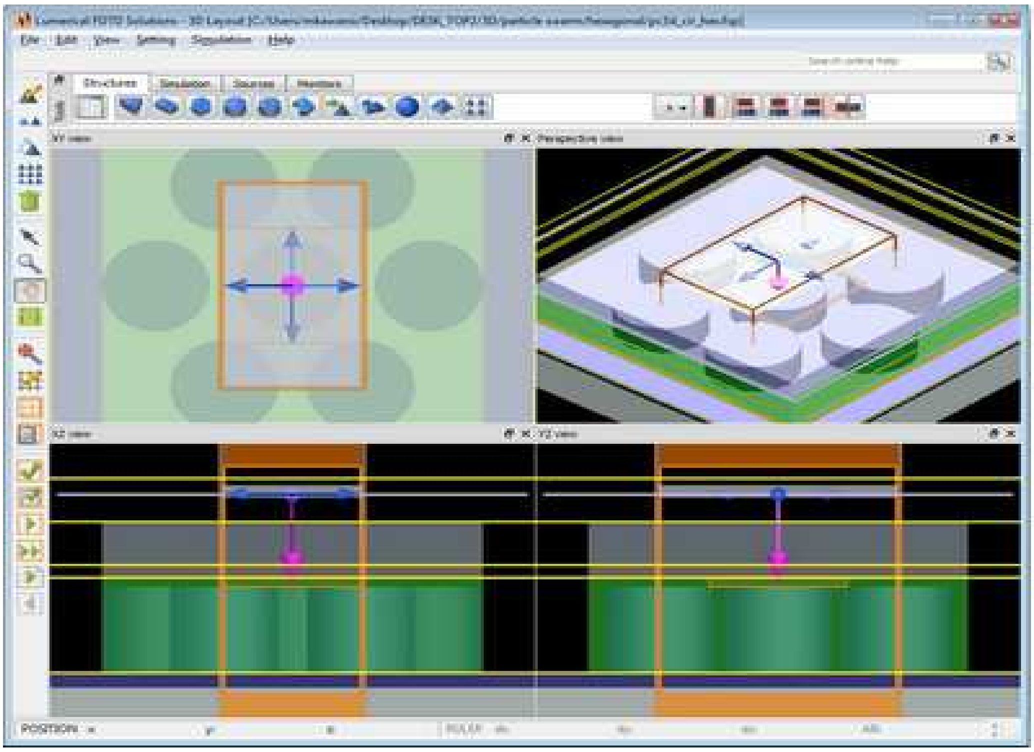


Figure 4.2 Screenshot of solar_cell_organic_2D.fsp

4.3 STRUCTURE OF ORGANIC SOLAR CELL

To model the material dispersion of P3TH:PCBM, ITO, PEDOT:PSS and aluminum, the multi-coefficient model (MCMs) is used. This generalized material model provides much better fits to experimental data than conventional models like Drude and/or Lorentz. The solar spectrum range from 400nm to 700nm. The glass and nc-ZnO are considered to be perfectly transparent and their refractive indices are taken.

4.4 SIMULATIONS

The Perfectly Matched Layer (PML) boundary conditions are used for upper and lower boundary and Periodic boundary conditions are used for the side boundaries to model the periodic nature of the photonic crystals. To precisely define a position of boundary between two medium, for example between P3HT:PCBM and PEDOT:PSS, we use override regions across the boundary. For example, the override region named "mesh_3" in the simulation file solar_cell_organic_1D.fsp, is used for defining the position of the boundary between P3HT:PCBM and PEDOT:PSS.

4.5 SOURCES

To model the sunlight, a normally incident plane wave with a wavelength range from 400nm to 700nm is used.

4.6 MONITORS

To calculate the power absorbed in the P3HT:PCBM, two power monitors are used. One, named monitor_3, is located at the boundary between P3HT:PCBM and PEDOT:PSS and the other, named monitor_4, is located at at the boundary between P3HT:PCBM and nc-ZnO. Using a script function "transmission", the absorbed power P_{abs} (λ) can be easily calculated by:

$$P_{abs}(\lambda)=\text{-transmission (monitor\_3) - (-transmission (monitor\_4))} \qquad (1)$$

If we use monitor_1, 2 and 3 with the transmission function, we can also calculate the light absorption in ITO and PEDOT:PSS layer. Furthermore, to calculate the absorption profile within the 1D PCOSC, we use a power monitor and an index monitor named *profile* and *index*, respectively.

4.7 SIMULATION RESULTS

In this section, it is calculated that the light absorption of the PCOSC and show an absorption enhancement caused by the trapped light as a leaky mode of the PC waveguide structure. We also calculate the light absorption in ITO and PEDOT:PSS layer and show that nearly 20% of the whole absorption in the PSOCS is consumed in these layers. In addition, we calculate the absorption distribution which varies strongly depending on the wavelength. In the following examples, the thickness of the ITO and PEDOT:PSS are fixed to 157nm and 50nm, respectively, and that of P3HT:PCBM is fixed to 115nm for the flat solar cell and varies for the PCOSC so that its volume must be equal to that of the flat solar cell. In Figure 4.3, the x and y dimensions shows the width and height of the solar cell and the colors represent the different wavelengths absorbed by those regions as per the scale shown in the figure. The figure shows the PEDOT:PSS layer providing increased wavelength absorbing capability of solar cell.

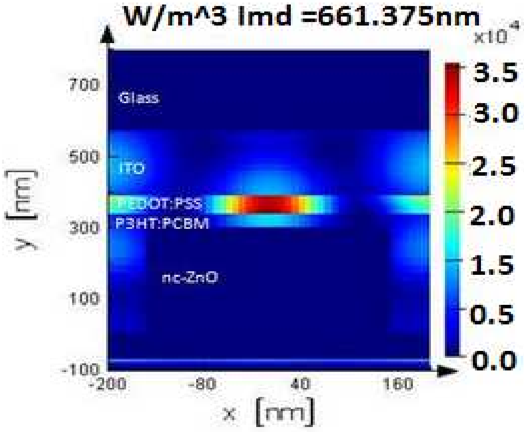
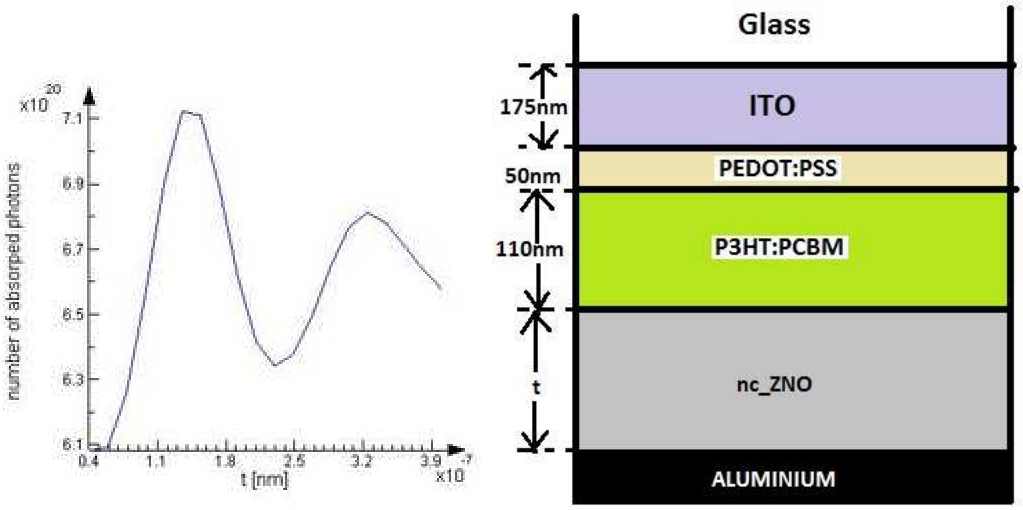


Figure 4.3 Light absorption profile within the PCOSC.

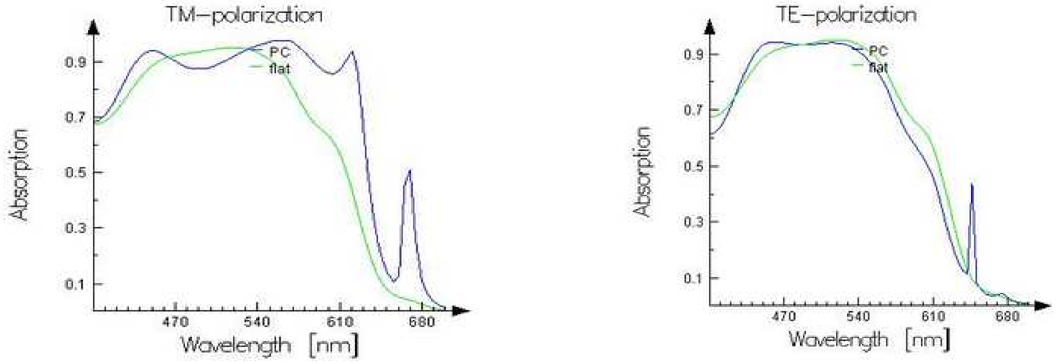
Before studying the absorption enhancement of PCOSC, we optimize the thickness of the optical spacer "nc-ZnO" of the flat solar cell so that we can evaluate the absorption enhancement of PCOSC compared with the flat solar cell. Figure 4.4 shows the number of absorbed photon as a function of the nc-ZnO thickness when AM1.5 sunlight illuminates the flat solar cell. As expected, the result oscillates as a function of the thickness and the maximum absorption is achieved around t=150nm. In the following results, when an absorption enhancement of PCOSC is discussed, it is compared with the flat solar cell with t=150nm.



(a) (b)

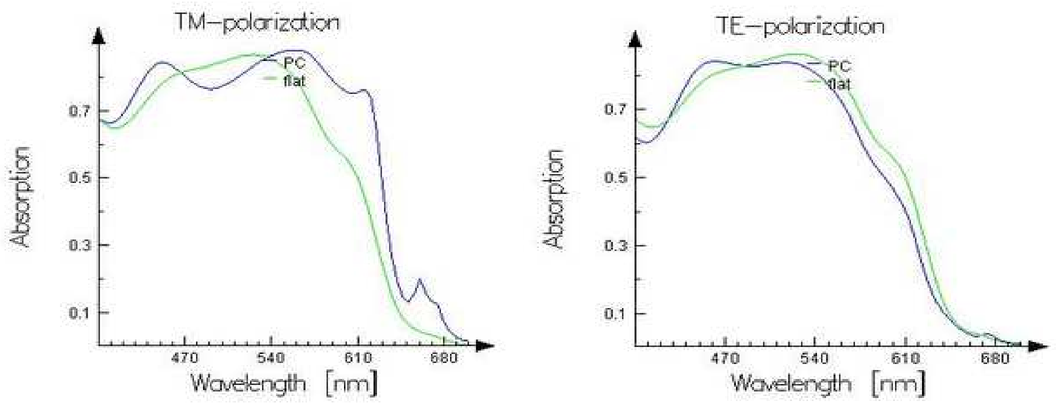
Figure 4.4 Number of absorbed photon of a flat solar cell as a function of nc-ZnO thickness t.

Next, it is calculated that the light absorption of 1D PCOSC and show the absorption enhancement by the PC structure. Here, the period, the width and the height of the PC are fixed to P=400nm, w=300nm and h=300nm, respectively and the thickness of the nc-ZnO is set to t=70nm (The optimization of structural parameters for PCOSC is performed in the next section using the particle swarm optimization). For reference, we firstly calculate the light absorption of the PCOSC when ITO and PEDOT:PSS are assumed to be perfectly transparent so that we can clearly see the resonant-like sharp absorption caused by the leaky mode. Figures 4.5 (a) and (b) are the results for, respectively, TM- and TE polarization where ITO and PEDOT:PSS are modelled as "Dielectric", i.e., n_{ITO} =1.45 and $n_{PEDOT:PSS}$ =1.8. The blue and the green line shows the result of PC and flat OSC, respectively. As shown in these figures, we can clearly see the resonant like absorption enhancement; for TM-polarization it appears at λ=621nm and 667nm, and for TE-polarization at λ=646nm. The fact that the sharp enhancement is caused by the leaky mode can be confirmed from the band diagram of the PC structure, where the bands intersect with Γ - point (kx=0) at those wavelength as indicated by green arrows. On the other hand, when a realistic model is taken into account, i.e. ITO and PEDOT:PSS are modelled with loss, the sharp absorption is significantly suppressed as shown in Figures 4.5 (c) and (d). Although the sharp effect for the TE polarization cannot be seen any more, we can still see the enhancement for TM polarization. The resonant peaks in the Figures 4.5 (a), (b), (c) & (d) show the increased particular frequency absorption by the solar cell.



(a) TM, no loss

(b) TE, no loss



(c) TM, with loss

(d) TE, with loss

Figure 4.5 Absorption within P3HT:PCBM (a) TM, no loss, (b) TE, no loss (c) TM, with loss, (d) TE, with loss.

Next, to study how much photon is absorbed in each layer, i.e. P3HT:PCBM, ITO and PEDOT:PSS layers, the absorbed photon flux within these layers for TM-polarization has been calculated as per in Figure 4.6. The absorbed flux can be calculated by multiplying the absorption in each layer with the AM1.5 solar spectral irradiance. As shown in this figure, at the wavelength λ=661nm where the absorption in the P3HT:PCBM is enhanced, the absorption photon flux within the ITO and PEDOT:PSS are also enhanced significantly. By integrating the absorbed photon flux over the wavelength from 400nm to 700nm, the number of the absorbed photon in each layer is calculated as $N_{P3HTPCBM}$= 7.36443e+020, N_{ITO}=1.21712e+020 and $N_{PEDOT:PSS}$=6.91428e+019. This means that ITO and PEDOT:PSS layer absorb nearly 20% of all the photon absorbed in the entire OSC structure.

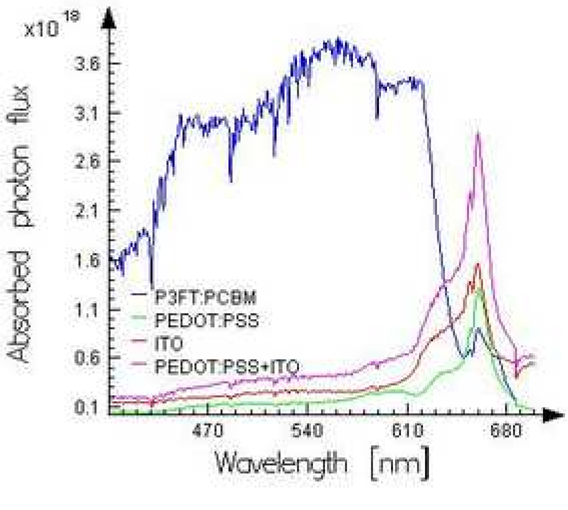
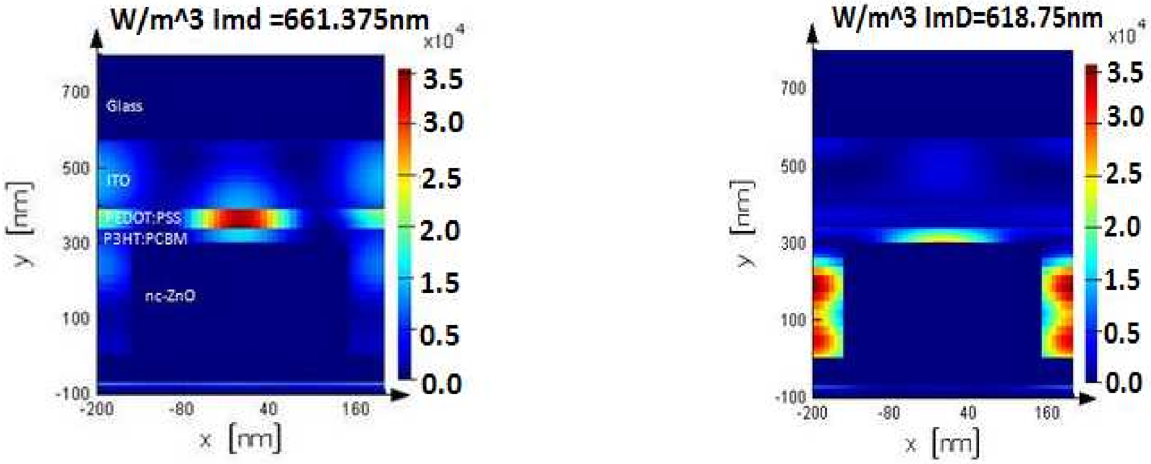


Figure 4.6 Absorbed photon flux in ITO, PEDOT:PSS and P3HT:PCBM layer.

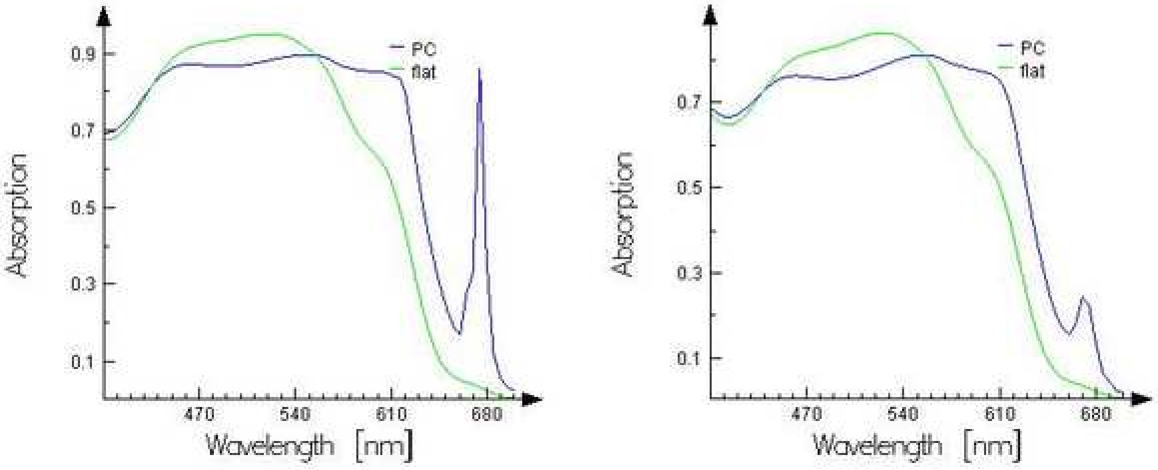
Figure 4.7 shows the absorption distribution inside the 1D PCOSC for TM polarization at different wavelengths of λ=661nm and λ=619nm. It can be seen that the location and magnitude of optical absorption varies strongly with wavelength on account of strong frequency dependence of photonic crystal structure.



(a) (b)

Figure 4.7 Light absorption profile inside the PC organic solar cell.
(a) λ=661.375nm, (b) λ=618.75nm

Figure 4.8 shows the absorption for a 2D PCOSC of hexagonal lattice. As the case of 1D PCOSC, we can also observe the sharp absorption enhancement in 2D PCOSC. The resonant peaks shows sharp absorption corresponding to those frequencies. The magnitude of relative absorption can be recorded from the Y axis from Figure 4.8.



(a) (b)

Figure 4.8 Absorption within P3HT:PCBM for 2D PCOSC. ITO and PEDOT:PSS have (a) no loss, (b) loss.

CHAPTER 5

CONCLUSION & FUTURE SCOPE

5.1 CONCLUSION

- It has been concluded that an absorption of the trapped light as a leaky mode of the PC waveguide structure has been enhanced. Before analyzing the absorption enhancement of PCOSC, the thickness of the optical spacer "nc-ZnO" of the flat solar cell has been optimized so that the absorption enhancement of PCOSC in comparison with the flat solar cell can be evaluated.

- Light absorption of 1D PCOSC has also been calculated and the absorption enhancement by the PC structure has been plotted.

- Also, the light absorption of the PCOSC has been first calculated when ITO and PEDOT:PSS are assumed to be perfectly transparent so that the resonant-like sharp absorption caused by the leaky mode can be clearly observed and analyzed. Although the sharp effect for the TE polarization cannot be seen any more but the enhancement for TM polarization has been observed.

- It has also been concluded that the location and magnitude of optical absorption varies strongly with wavelength on account of strong frequency dependence of photonic crystal structure.

- Also the absorbed flux has been calculated by multiplying the absorption in each layer with the AM1.5 solar spectral irradiance and concluded that ITO and PEDOT:PSS layer absorb nearly 20% of all the photon absorbed in the entire OSC structure.

5.2 FUTURE SCOPE

- As per the future perspective, the dimensions of the photonic crystal can be simultaneously optimized to further enhance the absorption capability of photonic cell.

- The efficiency of the solar cell as the function of photonic crystal dimensions can also be the future aspect of PC development.

- The various optimization techniques (like particle swarm optimization or Neural network algorithms) can be employed for optimizing the various parameters of the solar cell like optimizing the width "w" of the photonic crystal, the thickness of flash layer "df", and the thickness of the nc-ZnO "t".

- The light filters can also be employed for increasing the efficiency of solar cells that can be used for photovoltaic applications.

- Brag mirrors and brag gratings can also be employed to further enhance the absorption capability of solar cell.

LIST OF PUBLICATIONS

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