

# A solar cell (the photovoltaic cell) - essay



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A solar cell or the photovoltaic cell is an electrical device that converts light energy directly into electricity. This cell when exposed to light can generate and support an electric current without being attached to any external voltage source. The solar cell uses the photovoltaic effect to produce electricity. The word "Photovoltaic" comes from the Greek word meaning "light", and from the word "Volt", which is the unit of electro-motive force also the word "volt" comes from the last name of the inventor of the battery (electrochemical cell), the Italian physicist Alessandro Volta. Thus we get the term "photo-voltaic".

The photovoltaic effect, in brief, is a process in which electric current is produced in a material upon exposure to light. The photovoltaic effect being directly related to the photoelectric effect is actually a different phenomenon. In photovoltaic effect, the light is incident upon the material surface; the electrons present in the valence band of the atom absorb energy from the light and jump to the conduction band (band theory). Now these electrons are attracted by a positively charged electrode and thus the circuit is completed and the light energy is converted into electric energy. On the other hand, in photoelectric effect, the electrons are ejected from a material's surface upon exposure to radiation.

Photovoltaic systems are extraordinary and very useful with a huge list of advantages. The reason they are so unique is they have no moving parts (in the classical mechanical sense) to wear out. There are no fluids or gases (except in hybrid systems) that can leak out. The best part about these is that they need no fuel to operate. Having a rapid response, they achieve full output instantly. These cells can operate at moderate temperatures

producing no pollution while producing electricity, although waste products from their manufacture and toxic gases in the event of catastrophic failure and disposal may be a concern. Solar cells require little maintenance if properly manufactured and installed.

Silicon, the second most abundant element in the earth's crust can be used to make these cells. Thus, their production is possible on a large scale with an added advantage of them being modular, permitting a wide range of solar-electric applications such as:

- 1) Small scale for remote applications and residential use.
- 2) Intermediate scale for business and neighborhood supplementary power.
- 3) Large scale for centralized energy farms of square kilometers size.

Solar cells have a relatively high conversion efficiency giving the highest overall conversion efficiency from sunlight to electricity yet measured. This gives them wide power-handling capabilities, from microwatts to megawatts. Clearly, photovoltaic cells have an appealing range of characteristics. [1]

## **1. 1 HISTORY**

The physical phenomenon responsible for converting light to electricity-the photovoltaic effect-was first observed in 1839 by a French physicist, Edmund Becquerel. Becquerel noted that a voltage appeared when one of two identical electrodes in a weak conducting solution was illuminated. The Photovoltaic effect was first to be noticed and researched in solids, e. g. selenium, in the 1870s. However, it was in 1883 Charles Fritts built the first solid state photovoltaic cell; he coated the semiconductor selenium with an

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extremely thin layer of gold to form the junctions. The device was only around 1% efficient. In 1888 Russian physicist Aleksandr Stoletov built the first photoelectric cell based on the outer photoelectric effect discovered by Heinrich Hertz earlier in 1887.

The first practical photovoltaic cell was developed in 1954 at Bell Laboratories by Daryl Chapin, Calvin Souther Fuller and Gerald Pearson. A diffused silicon p-n junction was used by them; this junction could reach 6% efficiency, as compared to the selenium cells in which it was difficult to reach 0.5%. At first, cells were developed for toys and other minimal uses, since the cost of the electricity they produced then was very high; i. e. a cell that produces 1 watt of electrical power in bright sunlight cost about \$250, compared to \$2 to \$3 per watt for a coal plant. [2]

In 1958, the U. S. Vanguard space satellite used a small (less than one-watt) array of cells to power its radio. These cells functioned so well that the space scientists soon realized the Photovoltaic could be a very effective power source for many space missions. Technological development of the solar cell has been a part of the space program ever since then. Besides the space programs, another source is the transistor industry has contributed greatly to solar-cell technology. Transistors and PV cells are made from similar materials, and their workings are determined by many of the same physical mechanisms. A great amount of research and development has been done in improving and developing the ever-useful transistor, and there has been a regular discovery of valuable information in relation to solar cells. This situation has reversed in recent times and much of the research happening in PV is affecting transistor technology.

## **1. 2 EFFICIENCY OF SOLAR CELLS**

Today, photovoltaic systems are capable of transforming one kilowatt of solar energy falling on one square meter into about a hundred watts' of electricity. One hundred watts can power most household appliances like television, stereo, or a lamp etc. . In fact, on a standard basis a roof covered with solar cells facing the sun in a typical home provides about 8500-kilowatthours of electricity annually, which also is almost equal to a average household's annual consumption on electricity. On comparison, a present-day, 200-ton electric-arc steel furnace, demanding electricity worth 50, 000 kilowatts, would for a PV power supply, require about a square kilometer of land. Certain factors make capturing solar energy difficult. Apart from the sun's low illuminating power per square meter, sunlight is discontinuous and is affected by time of day, climate, pollution, and season. Power sources based on photovoltaic require either back-up from other sources or storage for times when the sun is obscured. Moreover, the cost of a photovoltaic system is very high (electricity from PV systems in 1980 cost about 20 times \* that from conventional systems powered by fossil fuels). Thus, solar energy for photovoltaic conversion into electricity is abundant, inexhaustible, and clean; yet, on the other hand it also requires special techniques to gather enough of it effectively.

When sunlight is incident on the solar cell, most of the energy is lost even before it can be converted to electricity. Maximal sunlight-to-electricity conversion efficiencies for solar cells range up to 30% (and even higher for some highly complex cell designs), but typical efficiencies are 10%-15%. Most current work on cells is directed at enhancing efficiency while lowering

cost. Certain physical processes limit cell efficiency-some are inherent and cannot be changed; many can be improved by proper design.

Reflection is the first factor that reduces the efficiency of the cell. Normal, untreated silicon reflects 36% (or more) of the sunlight that strikes it. This would be a horrendous loss in terms of efficiency. Fortunately, there are several ways of treating cell surfaces to cut reflection drastically. By dint of these methods, reflection can be lowered to a quite manageable 5% or so.

The second factor affecting the electricity production and then, in turn, the efficiency of the cell is the intensity of light falling on it. Now, this light can be of two types-

-Light that is not energetic enough to separate electrons from their atomic bonds.

-Light that has extra energy beyond that needed to separate electrons from bonds.

Both of the above types of light contribute in reducing the efficiency of the cell. Light entering a solar cell can-

- a. Go right through it.
- b. Become absorbed, generating heat in the form of atomic vibrations.
- c. Separate an electron from its atomic bond, producing an electron-hole pair.

d. Produce an electron-hole pair but have an excess of energy, which then becomes heat.

Only (c) is a near-perfect means of transforming sunlight into electricity.

Since the sun's spectrum has a wide variety of energies and intensities, the key is to match a material and its characteristic band gap energy with the spectrum so that the maximum amount of energy in the sun's spectrum falls just above the characteristic energy.

The third factor that reduces the efficiency of the cell is electron-hole recombination.

There are two ways in which recombination of electrons and holes occurs, which can be characterized as direct and indirect recombination.

-Direct Recombination: Direct recombination is relatively rare. It happens when an electron and a hole randomly encounter each other, and the electron falls back into the hole. Thus the material's original bonds are reasserted, and the electron's and hole's energies are lost as heat.

-Indirect Recombination: Indirect recombination can occur in many ways. ("Indirect" means that the electron and hole do not just run into each other and combine-the interaction is influenced by further circumstances.)

Contrary to what one might expect, indirect recombination is much more of a problem in solar cells than direct recombination.

Resistance is a factor which reduced efficiency of almost all known electrical appliances and the solar cell is no different. Resistance losses in solar cells

occur predominantly in three places: in the bulk of the base material, in the narrow top-surface layer typical of many cells and at the interface between the cell and the electric contacts leading to an external circuit. Resistance losses lower voltage and enhance the chances of recombination of charges, reducing current. Usually it is better to highly dope silicon to reduce resistance as highly doped silicon has numerous free carriers to conduct the current.

After considering the various factors discussed, we can actually look forward to see and study the construction of the solar cells with maximum possible efficiency. [3-10]

### **1. 3 types AND GENERATIONS of solar cells**

Solar cells can be of many types as we know them. Today's modern technology has allowed us to be able to study each in detail and help with improving energy output and increasing efficiency.

There are three types of solar cell-

1. Amorphous cells,
2. Polycrystalline
3. Monocrystalline.

Amorphous, also known as the thin-film solar cells are more commonly seen in devices like toys, calculators etc. Monocrystalline solar cells are cut from one silicon ingot which is got from a single large silicon crystal.

Polycrystalline cells are cut from an ingot derived from many smaller crystals.



Mono cells are made by growing an ingot of the silicon crystal from a smaller crystal, hence the name 'mono-crystalline' or single-crystal. This ingot is then trimmed and sliced into wafers.

In case of polycrystalline cells, molten silicon is poured into a square mould allowing it to set. Now silicon cools and sets at different rates, that is, the inside cools slower than the outer part and there is no seed crystal to grow the new material. This uneven cooling itself creates multiple crystals within the block thus giving it the name of poly-crystalline or multi-crystalline. Due to its multifaceted surface, this type of solar cell is a better performer even in dim light conditions giving greater wattage even from a small surface area.

Amorphous cells are made by depositing a thin sheet of silicon over a surface like steel. The panel we get is a single piece and individual cells are not visible. These cells do not have a high efficiency and thus give a lesser investment for our investment.

Apart from this solar cells can be divided into three generations, being:

– **1st generation**

– **2nd generation**

– **3rd generation**

First-generation cells are based on expensive silicon wafers and makeup 85% of the current commercial market. Second-generation cells are based on thin films compounds such as amorphous silicon, or copper indium selenide. The materials are relatively cheap, but research is needed to raise

the efficiency of these cells if the cost of delivered power is to be reduced. Third-generation cells have shown a dramatic increase in efficiency that maintains the cost advantage of 2nd generation materials. Their design may make use of carrier multiplication, hot electron extraction, multiple junctions, sunlight concentration, or new materials.[11]

### **First generation solar cells:**

These are the dominant type of cells available in the commercial market. A crystalline silicon wafer is used for the production of these cells. They tend to have a large surface area and a single layer p-n junction diode. Being so widely used, these cells have their own advantages and disadvantages. On the pros side, these cells have a broad spectral absorption rate and also have high carrier mobility. But these cells require expensive manufacturing technologies and also growing ingots is a very intensive process. Another disadvantage we can usually observe in these cells is that it is relatively easy for an electron to encounter a hole and thus that leads to recombination instead of electricity production. Most of the energy from a high energy photon is usually lost as heat.[12]

### **Second generation solar cells:**

Second generation solar cells are mounted on glass substrates. The production costs that were plaguing first generation solar cells find some relief with the second generation. There are many companies who desire to release second-generation thin-film solar cells to the public. The material used in second generation solar cells are normally; amorphous silicon, micro-crystalline silicon, cadmium telluride (“ CadTel”) and copper indium selenide/sulfide[14].

We see a potential for cost advantages in this generation over crystalline silicon because of various reasons. There is a lower material use along with fewer and simpler manufacturing steps. These cells also have the perfect band gap for solar energy conversion.[13][14]

### **Third generation solar cells:**

The third generation cells are very different from the previously discussed cells. They do not rely on a p-n junction to separate photo-generated charge carriers but are based on a silicon substrate with a coating of nanocrystals. The third generation is the future of solar cells and the cheapest of them all. They are exactly what the sun-powered industry needs for renewable and efficient power sources. As solar cell technology continues to grow, our solar conversion efficiency will continue to rise and production expenditure will continue to drop. The third generation solar cells focus on reducing manufacturing cost and enhancing the performance of 2nd generation solar cell technology. Nanotechnology is one area that is being researched upon by this new generation of cells. Nanotechnology is being used to improve the basic solar cell to have improved electrical performance which also makes it more cost efficient. [15, 16]

## **1. 4 POLYMER SOLAR CELL AND ITS DEVELOPMENT**

One of the unique 3rd generation solar cells we know today is the polymeric solar cell. usually consist of an electron- or hole-blocking layer on top of an indium tin oxide (ITO) conductive glass followed by electron donor and an electron acceptor (in the case of bulk heterojunction solar cells), a hole or electron blocking layer, and metal electrode on top.

During the last 30 years the polymer solar cell has developed from an inefficient light-harvesting device with almost no lifetime to a device that may be introduced to the commercial market within a short span of years. Today scientists are working with a lot of different types of polymer solar cells and since it will be too comprehensive to deal with all of them, only one type will be treated in this report. The type of solar cell which will be treated is a polymer/fullerene bulk hetero-junction solar cell. This type of polymer solar cell consists of 6 layers: Glass, ITO, PEDOT: PSS, active layer, calcium and aluminum.

The glass serves as a supporting layer for the solar cell and the only demand glass has to fulfill is that it does not absorb light in the visible area, since the solar cell uses this light to generate power. Other and more flexible types of supporting layers, like transparent polymers, can also be used. The focus of this report will not lie on the supporting layer and therefore the use of other types of supporting layers will not be discussed any further.[18]

ITO (indium tin oxide) and aluminum serve as the electrodes in the solar cell. Beyond that, the ITO and Aluminum are also used to generate a built-in electric field caused by the difference in the metals' work functions. This electric field is used to dissociate the excitons, which are generated when the active layer absorbs light, and afterwards to pull the charge carriers out from the active layer. Like glass the ITO layer is transparent in the visible area.

PEDOT: PSS (poly[3, 4-(ethylenedioxy)-thiophene]: poly(styrene sulfonate)) and calcium are two materials which are introduced into the solar cell in order to increase the built-in electric field and thereby improve the

performance of the solar cell. The active layer in this polymer solar cell consists of a blend between the conjugated polymer MEH-PPV ((poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene])) and the modified fullerene PCBM (1-(3-Methoxycarbonylpropyl)-1-phenyl-[6,6]C<sub>61</sub>). MEH-PPV is the absorbing part of the active layer and PCBM is introduced into the layer to make the dissociation of the excitons more effective.

In bulk heterojunction polymer solar cells, light generates excitons with subsequent separation of charges in the interface between an electron donor and acceptor blend within the device's active layer. These charges then transport to the device's electrodes where these charges flow outside the cell, perform work and then re-enter the device on the opposite side. The cell's efficiency is limited by several factors especially non-geminate recombination. Hole mobility leads to faster conduction across the active layer.[29][30]

By simply blending polymers (electron donors) with fullerene (electron acceptor) in organic solvents, a self assembling interpenetrating network can be obtained using various coating technologies ranging from laboratory-scale spin coating or spray coating to large-scale fabrication technologies such as inkjet printing[20, 21], doctor blading [17], gravure[23], slot-die coating[24] and, exographic printing[25].

In the last few years, several effective methods have been developed to optimize the interpenetrating network formed by the electron donor and acceptor, including solvent annealing (or slow-growth)[25], thermal annealing[26-28] and morphology control using mixed solvent mixtures[29]

or additives [30] in the solutions of donor/acceptor blends. Poly (3-hexylthiophene)(P3HT) in particular has been subject to increasing interest in the polymer research community, but significant progress has also been made in developing new active-layer polymer materials [19, 30-37]. Since around 2008, the efficiency of PSCs has risen to 6% using new conjugated polymers as electron donors [34].

Although progress has been impressive, there is still much to do before the realization of practical applications of PSCs. Many factors need to be taken into account in efficiently converting sunlight into electricity.

Figure 2: Shows the energy levels in a polymer solar cell. ITO(indium tin oxide) is used as the high work function electrode and Al is used as the low work function electrode. (a) displays the energy levels before the polymer solar cell is assembled. (b and c) shows the energy levels after assembling. In (b) the polymer is an insulator and therefore the electric field changes linearly through the cell. The polymer used in (c) is a hole conducting polymer and therefore a Schottky junction will be formed between the polymer and the low work function electrode.

The absorption range, the photon-electron conversion rate and the carrier mobilities of the light-harvesting polymers are among the crucial parameters for achieving high-efficiency solar cells. Furthermore, fabricating large area devices without significantly losing efficiency while maintaining long lifetime of the device remains challenging.[38] [39]

Therefore, a major challenge lies in fabricating polymer solar cells, in which free-charge-carrier generation is a critical step. Fortunately, it has been

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found that efficient charge transfer can take place between materials, that is, donor and acceptor molecules, with suitable energy level offsets. The strong electric field at the molecular interface of two materials with different electrochemical potentials is capable of separating the excitons into weakly bounded Coulombic pairs, and thereafter separated charge carriers. In cases where the donor and acceptor molecules form an intimate contact in blend films, efficient charge transfer takes place with an efficiency approaching 100%.

The short exciton diffusion length which is much smaller than the necessary film thickness for effective optical absorption, has limited the external quantum efficiency (EQE) and hampers the efficient utilization of the photogenerated excitons in organic photovoltaics.

A major breakthrough was achieved with the bulk heterojunction (BHJ) concept, where the nanoscale phase separation creates donor/acceptor interfaces for exciton dissociation via efficient charge transfer from donor to acceptor throughout the film. The concepts of donor/acceptor and BHJs, thus, establish the cornerstones of polymer solar cells.

Diagram of a polymer-fullerene bulk heterojunction.

The bulk-heterojunction concept. After absorption of light by the photoactive material, charge transfer can easily occur due to the nano-scopic mixing of the donor and acceptor (solid and dashed area). Subsequently, the photo generated charges are transported and collected at the electrodes. Here highest occupied molecular orbital is abbreviated as HOMO and the lowest unoccupied molecular orbital as LUMO.

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Despite the high attainable EQE, overall power conversion efficiencies (PCE) reported are still low, due to the inferior charge-transport properties and limited spectral absorption range of the polymer active layer. On one hand, endeavors in synthesis and development of novel low-band-gap polymers are being carried out to harvest the major part of the solar spectrum. [40-46]

On the other hand, film-growth dynamics of polymer blends via solution processes has become one of the central topics to derive maximal efficiency from bulk-heterojunction structures. Meanwhile, precise efficiency measurements provide solutions to the spectral mismatch between the solar spectrum and polymer absorption, offering accurate evaluation of novel photoactive materials.

High internal quantum efficiencies can be expected, provided that efficient donor-to-acceptor charge transfer and transport in the bulk heterojunctions occurs. A suitable energy-level alignment between the donor and acceptor to provide the driving force morphology plays a decisive role linking the optoelectronic properties and device performance to the fabrication processes. In addition to experimental results, simulation techniques have also been applied to predict the optimal morphology, yielding results that are consistent with the experimental conclusion that a nanoscale phase separation with a bi-continuous pathway toward the electrode is desired. Fabrication parameters such as solvent selection and annealing treatment are the most critical factors in film morphology.

However, additive incorporation also showed significant benefits toward improving device performance. The overall effects of morphology



manipulation assist in forming an interpenetrating network of donor and acceptor molecules, facilitating both charge transfer and carrier transport. Lateral phase separation has been observed and well-understood in several systems. Beyond that, the ingredient distribution of the donor and acceptor molecules along the cross-section of blend films, that is, vertical phase separation has been observed recently in the nanoscale film morphology, which intuitively governs the charge transport and collection. Thus, an ideal morphology consists of phase separation laterally and vertically, which should both be optimized for satisfying device performance.[47, 50-52]

A variety of post-treatment methods can alter the optoelectronic properties of the polymer-blend films. Annealing processes in polymer solar cells can be divided into two categories: thermal annealing [53, 57, 58] and solvent annealing.[48, 59-61] Both techniques concentrate on improving the nano scale lateral phase separation of both the crystalline P3HT aggregates and PCBM domains. Thermal annealing can be applied either on the final device (post-annealing) or on the polymer film only (pre-annealing). The annealing temperature and time are the two most critical parameters in this approach. However, the selection of solvent as well as metal electrodes could also affect the ultimate device performance.

Solution processing has many advantages over other film fabrication technologies, which usually require complicated instruments as well as costly and time-consuming procedures. Therefore, solution processing has developed into the most favored methodology for fabricating organic optoelectronic devices. Solution processing also allows the freedom to control phase separation and molecular self-organization during solvent

evaporation and/or film treatment. The solvent establishes the film evolution environment, and thus has foreseeable impact on the final film morphology. Selection and combination of solvents have been shown to be critical for the morphology in polymer-blend films, and are well-documented in the literature. [48, 49]. Spin-coating from single-solvent solutions results in thin films, which possess optoelectronic properties determined by the solution parameters and the spin-coating process, for example concentration, blending ratio, spin speed and time, etc. Meanwhile, solvent properties, such as boiling point, vapor pressure, solubility, and polarity, also have considerable impact on the final film morphology. [62-75]

## **1. 5 Work function of solar cells**

### **1. 5. 1 Work function of material**

The work function is the minimum energy needed to move an electron from the Fermi energy level,  $E_F$ , to vacuum energy,  $E_{vac}$ .

The work function varies by using different materials and also by doping. It is lower for n-type semiconductor than for p-type because Fermi levels within the band gap of a semiconductor depends upon doping. Where are work functions of the n-type and p-type materials respectively.

Junctions having different work functions give way to an electrostatic field.

### **1. 5. 2 Metal-semiconductor junction**

Metal-semiconductor junction is the simplest type of charge separating junction.

If we have an n-type semiconductor of work function metal of work function, such that, it is called a Schottky barrier.

When metal and semiconductor are separate from each other, the Fermi levels will look like in fig. 5(a). But when they are in contact (electronic), these levels will line up. The exchange of charge carriers across the junction results in this, with the consequence that the layers approach the equilibrium (thermal). The energy at the conduction band edge at the interface between semiconductor and metal is higher than in the bulk of the semiconductor. The electrostatic potential energy is shown in fig. 5(b) by the change in  $E_{vac}$ .

The space charge region or depletion region is the region where there is a net charge.

As  $E_{vac}$  changes, so must the conduction and valence band energies, and that too by the same amount (proportionality). This happens because the electron affinity and band gap are invariant in the semiconductor, and is called band bending.[76]

### **1. 5. 3 p-n heterojunction**

A heterojunction consists of two different materials with different band gaps and these can also be either p-n or p-i-n junctions. Devices based on heterojunctions can improve carrier collection and thus efficiency. Due to change in the band gap, a discontinuity exists in the conduction and valence band at the junction.

The potential step will affect the effective fields for the two carrier types in different ways. Usually, one carrier type is assisted by the field change, while the other is opposed. In fig. 6(b), the field that drives electrons to the n side is increased, while the field driving holes towards the p side is decreased.

[76]

We know that the standard form of an organic photovoltaic cell is based upon sandwiching a thin semiconducting organic layer(s) between two conducting layers having different work functions here we have higher work function conductors typically made of gold or ITO and lower work function conductors typically made of aluminum or calcium.

We have already discussed in section 1. 2 how the efficiency of solar cell can be improved, here we will consider mathematical expression of efficiency. Efficiency is defined as measures the amount of energy converted to electric current relative to the total energy incident upon the cell, it is designated with Greek letter  $\eta$ . The formula for calculating efficiency is:

$$\eta = J_{sc} \times V_{oc} \times FF,$$

where  $J_{sc}$  is the short-circuit current (when there is maximum current flowing and no voltage difference across the circuit),  $V_{oc}$  is the open-circuit voltage (when there is no current flowing), and FF is the fill-factor (the actual power relative to the theoretical power produced by the cell).

To increase the efficiency of Polymer Solar cells, we need to improve these 3 factors.  $J_{sc}$  is primarily affected by band-gap, carrier mobility, and film formation properties of the active layer.  $V_{oc}$  is primarily affected by the

material band-gap and the device structure. FF, is particularly difficult to predict and design, but seems related to the relative motilities' of the electrons and holes.[77-80]

## **1. 6 Inverted Polymer Solar Cells**

The regular device structure for polymer solar cells is indium tin oxide (ITO), where a p-type layer is used for anode contact, and a low-work-function metal as the cathode. Both the p-type layer and the low-work-function metal cathode are known to degrade the device lifetime. [106-108] The p-type layer is potentially detrimental to the polymer active layer due to its acidic nature, which etches the ITO and causes interface instability through indium diffusion into the polymer active layer.

Low work- function metals, such as calcium and lithium, are easily oxidized, increasing the series resistance at the metal/BHJ interface and degrading device performance. In principle, ITO is capable of collecting either holes or electrons, since its work function (4. 5 to 4. 7 eV) lies between the typical highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) values of common organic photovoltaic materials. The polarity of the ITO electrode depends mainly on the contact