



**ENGR 232L:**  
**Engineering Materials**

**Final Term Paper**

**SOLAR ENERGY: MATERIALS FOR**  
**PHOTOVOLTAIC CELL**

**Advantages and challenges of silicon in the photovoltaic cells**

by

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## **Abstract**

Due to the high energy demands followed by the crisis of petroleum, the hope for the future lies in the renewable energy resources such as solar energy. Photovoltaic cells with materials involving, mainly silicon in both crystalline and amorphous form are used in this industry. This paper elaborates on the characteristic of both crystalline and amorphous silicon that makes it worth to use them in the photovoltaic cell. However, there are a lot of challenges involved in their use in the cell such as high manufacturing cost, loss of material for crystal silicon while issues affecting the efficiency negatively in terms of amorphous silicon. In response, solutions have been suggested in terms of both alternatives manufacturing methods and materials used in the photovoltaic cells. The paper further explains the pros and cons related to the suggestions involving changes in the production methods (Czochralski method) and pushes the idea of using new material such as organic materials involving polymers (P3HT/PCBM) along newly invented nanomaterial. The paper ends with introducing the concept of tandem cell comprising two distinct devices stacked on top of each other, which allows absorbing light with wider range of wavelength.

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## 1. Background:

Today, the nonrenewable energy resources such as petroleum, coal, natural gas are depleting at very high rate. Even though nuclear energy has been a consistent source of energy for a very long period, doubts have been raised about its continuation after the last year's Japan disaster. Due to this decrease in the traditional energy sources, the demand for the alternatives energy resources has started to rise. To meet this increasing demand with keeping environmental concerns in mind, people are thinking about increasing use of renewable energy sources such as wind and solar energy. Since the sun is an energy source, which will never get exhausted, it can be used without thinking about shortage of supply of sunlight. The amount of sunlight that falls on the surface of the earth and can be effectively used ranges in amounts of 89,000 terawatts per year. Thus, solar energy can be seen as an emerging source of energy.

During the last quarter of the century, solar generation of electricity has been proven technically feasible and reliable. Despite these advantages, the observation of the following diagram suggests that even after many years of invention of photovoltaic effect, its use to produce electricity has been very limited. A study by International Energy Agency (IEA) shown that from 1973 to 2008, the use of all renewable energy resources including solar, wind and heat have shown a dramatic increase [1]. However, the use of all of these renewable resources still only accounts for less than 1% of overall energy use. Even today, oil, coal and natural gas, which still counts for over 60% along with nuclear energy, have been the most used energy resources.

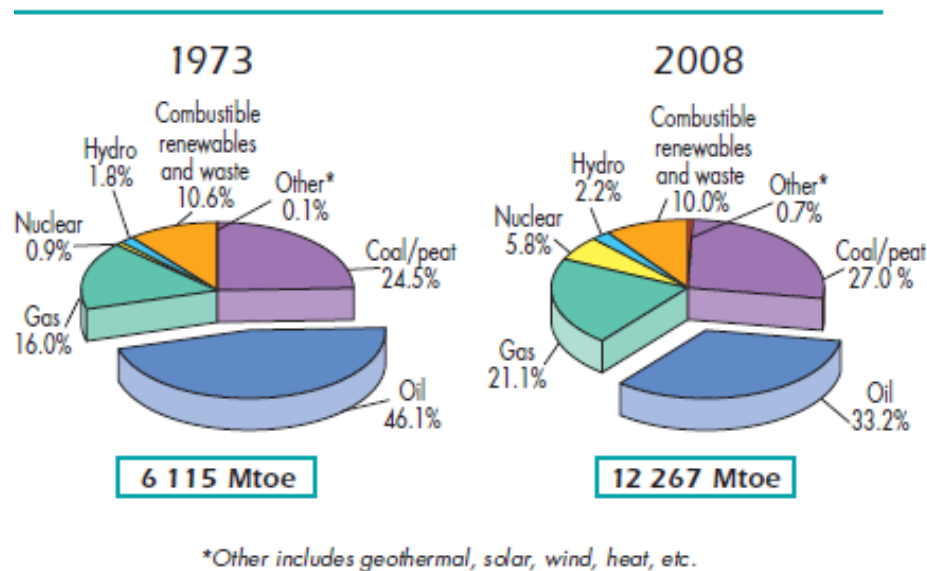


Figure 1: Total worldwide energy supply of 1973 and 2008 [1]

There are different ways of utilizing the natural sunlight. Solar technologies are broadly characterized into two different categories known as passive or active, depending on the way they capture, convert and distribute solar energy. Active solar technologies involve the use of solar panels and solar thermal collectors to use the solar radiation. Passive technologies basically include the building structure to provide sunlight to all rooms, where thermal and insulating mechanisms are built into the

house to generate proper heating and cooling system, all without the use of any extra apparatus. What I am mainly concerned about is active solar technologies involving photovoltaic effect.

So far, solar photovoltaic energy conversion has been used as the premium energy source in most of the orbiting satellites. Silicon has been the most used material in most of the successful photovoltaic cells. Two different forms of silicon, pure silicon and amorphous silicon are used to build the cells. However, the use of the photovoltaic cells has been limited due to high processing cost of high purity single crystal material used and the lack of effective mass production techniques used to produce thin silicon films. Though single-crystalline silicon solar cells have been most efficient and advanced of all cells, it is hard to implement them due to the cost factor. Thus, alternatives to silicon in the form of thin-film materials such as cadmium telluride and Copper-Indium:Diselenide (CIS) are being considered today. This overall paper further discusses in details, the advantages and challenges of using different forms of silicon in photovoltaic cells.

## **2. Types of photovoltaic cells**

Energy of the solar radiation is converted into electric energy through the photovoltaic effect. Edmund Becquerel was first scientist to discover the photovoltaic effect and it was observed in a liquid electrolyte. [2] Later work on Se, Cu-Cu<sub>2</sub>O, PbS, Tl<sub>2</sub>S, Ag<sub>2</sub>S, and many other materials known as photoconductors or phosphors showed that the photovoltaic effect is very common in some specific material. Later this photovoltaic effect was discovered in material such as silicon, GaAs and other material and its usefulness for technical applications such as solar energy was later developed.

A discontinuity or marked changes in the materials used have been found very common in all photovoltaic cells [3]. This discontinuity has been responsible for the creation of a potential, resulting in the separation of photo-generated charge carriers. This build-in potential is used for the power generation of the solar cell. According to the type of the change or discontinuity, there are two kinds of primary photovoltaic cells, homo-junction and hetero-junction.

The discontinuity in homo-junction cell is in the type of the conductivity of the material from n-type to p-type [4]. The region over this discontinuity change occurs is called as the p-n homo-junction. Homo-junctions are generally found in the elemental semiconductors such as Si and Ge, or the compound semiconductors such as GaAs and CdTe. Hetero-junctions are the combination of two different kinds of semiconductor in either a graded or abrupt fashion. The discontinuity in the hetero-junction photovoltaic cells occurs in the material characteristics such as carrier densities, electron affinity, conductivity, energy band gap along with dielectric constants. The examples of the hetero junctions are n-CdS/p-Cu<sub>2</sub>S, n-CdS/p-InP and many others. Along with these two kinds of discontinuities, one more type is also found in the cell with metal-semiconductor combination. This discontinuity created by certain metal-semiconductor combinations produces a sufficient enough potential to cause an asymmetric carrier flow and is designated as a Schottky diode. In this cell, the metal is applied as a thin transparent layer, while semiconductor is used to generate the excess carriers. The known Schottky diodes are n-GaAs/Au, n-Si/Cr(Cu) and p-Cu<sub>2</sub>O/Cu.

The most common material in which the photovoltaic effect occurs are semiconductors, which lie between metals and the insulators in terms of the conductivity. At low temperature, electrons in semiconductors are in energy level known as full valence band, where they occupy a lower, stable energy state. But increasing temperature allows more electrons to transit from the full valence band to the

conduction band. In this energy state, the electrons experience vibrations within the atomic lattice of the material. The energy required for this transition of the levels is known as band gap energy.

### **3. Photovoltaic material:**

To be practically useful and commercially reliable, the photovoltaic cells need to be affordable, efficient and stable. It is really important that the price of the photovoltaic cell is within the affordable range, so that it can compete with other source of energy. Furthermore, while building the acceptable solar cell, it is really important to keep in mind the length of operating life, which is usually set at about twenty years. While talking about the stability of the photovoltaic cells, is clear that a cell must remain in operating condition for a period of time such that the energy produced by the cell is appreciably greater than energy required for the production of the cell. In order for the photovoltaic cells achieve these goals, they needs to be constructed with the material that can satisfy these goals. The semiconductor used needs to have a low enough energy band gap to absorb the solar spectrum effectively and to control the electrical processes involved in energy conversion. Given this, it is very clear that the material used in the photovoltaic cells play a major role in its functioning.

Given a long range of material mentioned above, one might think that there is abundance of the material to be used in the photovoltaic cell, but it still remain true today that only a relatively small number of materials have met the basic criteria. Semiconductor and semiconductor compounds such as Si, GaAs, InP, CdTe, and CuInSe<sub>2</sub> are used in the single crystal cell, while hydrogenated amorphous silicon (a-Si: H), CdTe, and CuInSe<sub>2</sub> are generally use to produce the thin film with efficiency greater than 10%. Recent research has also investigated the use of multi-junction cells in which two (or more) different cells are used together, to produce the energy more efficiently [5]. One of the landmarks of 1988 was the achievement of a 31% efficient solar cell with a combination of a single-crystal GaAs (with efficiency of 27.2% when used alone) along with a back-contact single-crystal Si (with efficiency of 26% when used alone).

### **4. Silicon in photovoltaic cell:**

Among all of the materials listed above, silicon is the most commonly used material in the photovoltaic cells. It is also present in abundance in nature as silicon dioxide in sand and quartz, from which it is extracted by reduction with carbon.<sup>[6]</sup> In fact, silicon accounts for about 26% of the earth's crust. In the photovoltaic cells, two different forms of silicon are being used such as pure crystalline silicon and the amorphous silicon. Due to the change in the structure, there are a lot of difference in terms of physical properties of pure crystalline silicon and amorphous silicon.

#### **4.1 Pure Crystalline Silicon**

##### **4.1.1 Single crystalline silicon**

Pure crystalline silicon does not have the most desirable properties required for the photovoltaic cells. Thus, in order to use pure crystalline silicon effectively in the photovoltaic cell, it needs to go through a lot of processing. Though pure silicon is a bad conductor of the electricity, it can doped with material like phosphorous and boron, as discussed above. There are also other physical properties that characterize the silicon are discussed briefly below.

Energy band gap, which is the energy needed to shift electron from valence to conduction shell, is one of the characteristics that define the electrical properties. Silicon has energy band gap of about 1.1eV, which is sufficient enough to absorb most of the photon with the energy band gap higher than 1.1eV. However, as temperature increases, the band gap decreases allowing silicon of capable to absorbing photons with energy band gap less than 1.1 eV. The energy band gap height relationship with temperature

is given by:  $E_g(T) = 1.17 - \frac{4.73 \times 10^{-4} T^2}{636 + T}$  [7] Figure 4(a) represents energy bang gap as a function of decreasing temperature.

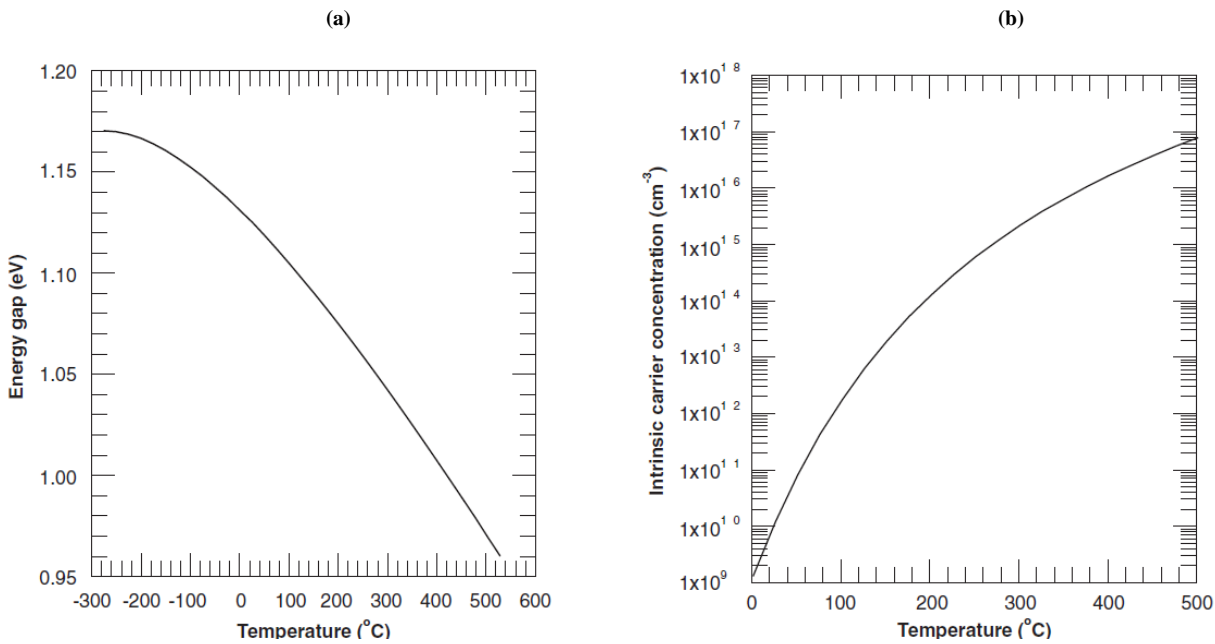


Figure 2: (a) Energy band gap [7] and (b) intrinsic carrier concentration [8] as function of decreasing temperature

Another important property that makes silicon worth to be used in the cell is the intrinsic carrier concentration. Intrinsic carriers are the silicon electron in conduction band. The concentration of intrinsic carrier is found as:  $n_i = 3.10 \times 10^{16} T^{3/2} e^{-1.206/kT}$ , where k is Boltzmann's constant [8]. The relationship between the intrinsic carrier concentration and temperature is given in figure 4(b).

Silicon has very high carrier mobility, the rate at which the carriers move under the influence of electric field, that differentiates it from other semiconductors. For low electric field, the drift velocity in terms of the electric field and the mobility is as:  $v_d = \mu E$ , where  $\mu$  is the mobility and  $E$  is electric field [9]. The figure nearby represent the carrier mobility in phosphorous and boron doped silicon.

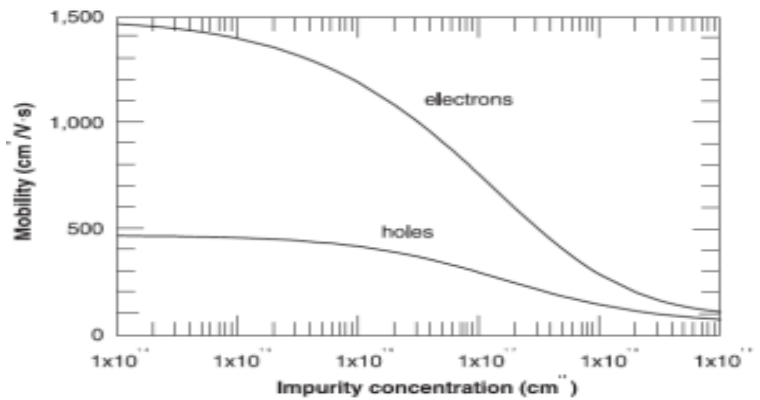


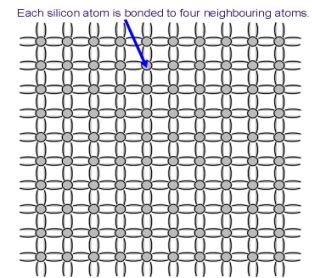
Figure 3: Carrier mobility in phosphorous and boron doped silicon [9]

One more characteristic that really influence the decision of using silicon over any other kinds of materials mentioned above is its non-hazardous properties. As silicon is a non-toxic material, it has very low effect on the environment. These all characteristic of silicon makes it worth to be used in the photovoltaic cell. Since almost all of the industries related to electronics and communication operate with silicon as their prime semiconductor material, there is already a large scope and wide array of technological tools for processing and manufacturing silicon according to specific needs.

According to measure of efficiency, which is determined by fill factor ( $E_f = V_{oc}/I_{sc}$ ), solar cells are divided into monocrystalline and polycrystalline cell. There is a trade-off between efficiency of photovoltaic cell and producing energy of cell. The brief details of these cells are discussed below.

#### 4.1.2 Monocrystalline cell:

Single crystal or mono crystalline silicon is a continuous crystalline material with no grain boundaries. The entire structure is one extensive crystalline structure. There is a uniform molecular structure for all the silicon atoms, with each of the four valence electrons of a silicon atom linked to another silicon atom, as shown nearby. This is most efficient of all available photovoltaic cells, with efficiency ranging within 25-30%. It is manufactured using the Czochralski method, which needs a huge amount of energy.



**Figure 4: The continuous structure of single-crystalline Silicon** <sup>[10]</sup>

In this method, silicon is extracted from silicon dioxide and melted in a quartz crucible along with the dopant material (phosphorous and boron) [11]. A single crystalline silicon seed is then dipped into the molten liquid to initialize crystallization. The seed is then pulled out slowly; the temperature and the rate of pull determines the rate of growth of the resulting mass of mono crystalline silicon, known as the ingot. This mass of crystal, which contains only mono crystalline silicon with dopants all throughout, is then cut into slices and these slices are further processed into very thin wafers, range in thickness from 200-300 micrometers [12]. The wafers are then coated with a special layer of anti-reflective material of silicon nitride. These wafers are connected together in either series or parallel, forming the solar panel, as shown.



**Figure 5: Monocrystalline solar panel**

#### 4.1.3 Polycrystalline cell

Polycrystalline silicon is made of several small grains of mono crystalline silicon, with several grain boundaries between the individual crystals. Polycrystalline cell, about 17% efficient, is most commonly prepared by using molten liquid silicon mixed with dopants [13]. Instead of crystallization, the molten liquid is cooled in a block-shaped cast. The rate of cooling determines the size of the crystal grains and the distribution of the dopants in the mixture. After cooling, the resulting ingot is sliced into thin portion, usually square in shape by passing the ingot through metal wires. These cells are connected together forming a polycrystalline solar panel. Thus, the manufacturing of polycrystalline silicon cells is much simpler and cheaper than that of mono crystalline silicon.



**Figure 6: Polycrystalline solar panel**



## 4.2 Amorphous Silicon:

Thin film solar cells are constructed from hydrogenated amorphous silicon (a-Si : H), consisting of an un-doped insulating region between doped p-type and n-type end regions. In the case of amorphous silicon, the principal carrier transport mechanism occurs due to the either diffusion or the drift collection under the influence of a large electric field [14]. However, the consequence of drift collection is that collection of the photo generated current becomes voltage-dependent, influencing the fill factor and thus, the efficiency. Thus, most of the thin film solar cells made from amorphous silicon are based on the p-i-n devices, where light is absorbed through i-layer under the influence of the electric field. Figure 7(b) represents photon current increase due to the increase in optical path length. The absorption coefficient for amorphous silicon,  $\alpha$  ( $\alpha(1/\mu\text{m}) = \alpha_0 \exp [(E - E_g)/E_0]$ , where  $E_g$  is band energy gap and  $E$  is photon energy) is sufficiently large that cells need be only 1-2  $\mu\text{m}$  thick to absorb virtually all of the light above the 1.7 eV absorption edge [15]. This is shown through the figure 7(a), which represents the optical absorption coefficient versus photon energy for GaAs, single crystal silicon and amorphous silicon. Furthermore, amorphous films are free of the grain boundaries. Efficiency of these cell as high as 12% have been obtained for single-junction cells, making this solar cell a major competitor to crystalline solar cells.

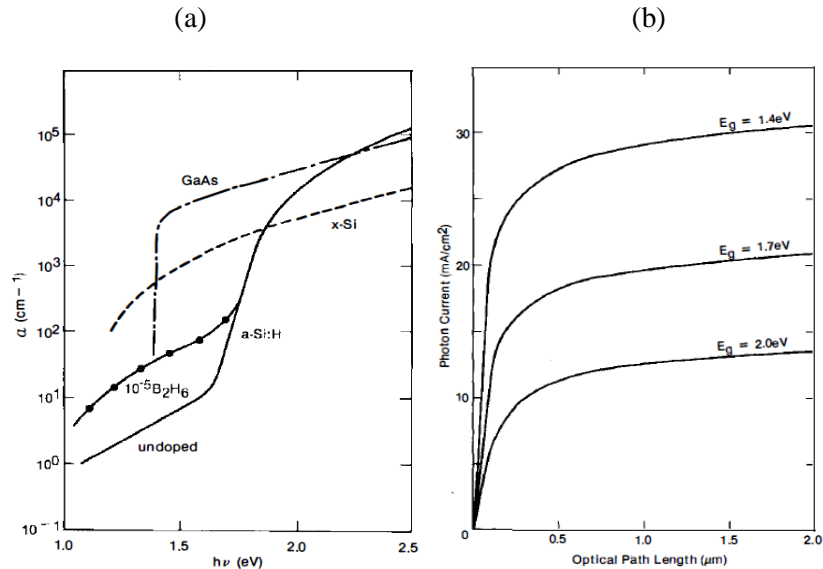


Figure 7: (a) Optical absorption coefficient vs photon energy; (b) Photon current vs optical path length

One more advantages of thin film solar cells is their processing cost. Unlike the crystalline solar cells, the thin films are developed through different processes. Most commonly, the silicon is deposited by chemical vapor deposition, typically plasma-enhanced (PE-CVD), from silane gas and hydrogen gas [16]. Silicon is deposited on glass, plastic or metal which has been coated with a layer of transparent conducting oxide (TCO). Another more advanced approach is the “ribbon growth” method in which silicon is grown directly as thin ribbons or sheets. The most commercially developed ribbon growth approach is EFG (edge-defined film-fed growth).

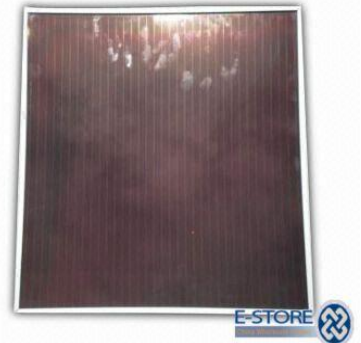


Figure 10: Amorphous silicon solar cells

## 5. Challenges of silicon in photovoltaic cells

Due to the efficiency, most of the solar cells are constructed using the single crystalline silicon. The effectiveness of monocrystalline solar cells mostly lies in the fact that it does not have the grain boundaries due to its continuous structure, which means the excited electrons move around the silicon structure without any grain boundaries to obstruct their movement. On the other hand, there lie several grain boundaries in the polycrystalline cells which inhibit the continuous flow of the excited electrons in the semiconductor, leading to a radical drop in efficiency to about 10-15% [17]. Therefore, research has been developed for finding the solar cell balancing the cost-effectiveness and performance. Even though a thin film solar cell made by amorphous silicon seems to be a good replacement, they are suffering in terms of efficiency, mainly due to the lack of a uniform crystalline structure. Some of these issues are discussed in details below:

### 5.1 Single Crystalline Silicon:

#### 5.1.1 Cost of processing:

The Czochralski method, which is used to manufacture the monocrystalline silicon cells, needs a lot of energy. Since single crystal silicon needs to be pure in order for its crystalline structure to be highly uniform, a lot of processing needs to bring it to that level. Silicon used for single crystal silicon may need to have an impurity concentration of as low as  $10^{-10}$  % [18]. Extremely precise control and balance of the single crystal silicon seed is required in order to generate an ingot that has monocrystalline silicon all throughout. Also, during the procedure, oxidation of the ingot is also an unavoidable consequence as oxygen combines with the silicon as well as the dopants on the surface of the ingot. This combined oxygen later on hampers the flow of charge carriers/electrons in the cell, decreasing the efficiency. This overall complicates the procedure, and hence, increases cost.

#### 5.1.2 Loss of material:

In order for the single crystal silicon to be modulus, it needs to be sliced in wafers of thickness ranging from 200-300  $\mu m$ . For this purpose, an inner diameter saw is used. This saw employs diamond particles on its blade for sawing the ingots into fine wafers [19]. It is difficult to employ any kind of saw mechanism, because at the desired thickness level of the wafers (200-300  $\mu m$ ), they tend to break easily. However, while the wafers are manufactured using this mechanism, about 50% of the produced silicon gets lost as sawdust, mainly due to the sawing in this process.

#### 5.1.3 Problems with absorption:

A general structure of the solar panel includes a glass on top for protection from wind, the photovoltaic cell with antireflective coating in the middle with a metal to support at the bottom. Each layer in the cells is characterized by a complex refractive index ( $\mathbf{N} = \mathbf{n-ik}$ ), where  $n$  is real refractive index of material and  $k$  is the extinction coefficient.

The absorption factor of the solar cells ( $\alpha$ ) is equal:  $\alpha = 4\pi k/\lambda$ . However, according to this equation, as the wavelength of photons increases, the absorption coefficient decreases [20]. Photons with short

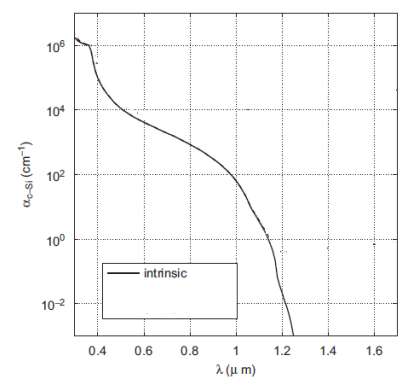


Figure 11: Absorption as a factor of wavelength [20]

wavelength ( $\lambda < 1.0$ ) have an energy larger than the band gap, which allows it to generate electron-hole pairs and is readily absorbed by the crystalline silicon. This wavelength of light/photons usually includes the infrared spectrum. However, long-wavelength photons ( $\lambda > 1.2 \mu m$ ) cannot generate electron-hole pairs and are hardly absorbed. Photons in the transition region of ( $1.2 \mu m < \lambda < 1.0 \mu m$ ) are weakly absorbed. This means, light with higher wavelength ( $\lambda > 1.2 \mu m$ ), is not utilized by the solar cell.

## 5.2 Polycrystalline silicon:

We know that, when the photon with different wavelength strike the surface of photovoltaic cell, it create an electron-hole pair. In the case of a hole formed at the p-n junction, electrons coming from the top surface are captured by the holes on the top surface and in the same way, the holes created in the bottom layers will capture the electrons coming from the junction. This overall decreases electron flow resulting in overall decrease in the current generated in the cell. This is a common problem with crystalline silicon cells because they are made thicker than other. Thus, a lot of recombinational loss occurs which decreases the overall efficiency.

The polycrystalline cell contains a certain degree of thickness, higher than that of monocrystalline cell. As these cells are made of several single-crystal molecules, it has a lot of grain boundaries, which are primarily composed of regular line defects: simple dislocations, partial dislocations, and stacking faults [21]. Two methods are used to measure the grain boundaries in the polycrystalline silicon, known as I-V deconvolution and charge emission. The first one involves the measurement of trans-barrier current, while the latter one is a high frequency barrier capacitance determination [22]. Among the two methods given below, the I-V deconvolution method is most used one. Here, the trans-barrier current is measured as:

$$J = \frac{A^*T}{k} \int_0^\infty n(E)D(E) dE$$

, where  $A^*$  is the effective Richardson constant. The supply function,  $n(E)$ , is calculated by appropriate  $k$  space integration, and the transmission probability,  $D(E)$ , is estimated using the WKB approximation [23]. This expression explains the inverse relationship between the grain-boundaries and the current flowing through the cell. When the grain boundary is associated with a dc bias, the above equation can be expressed as:

$$J = \frac{A^*T}{k} e^{-(\phi_B + \zeta)/kT} (1 - e^{-eV/kT}),$$

which shows that the quasi Fermi level at the grain boundary is pinned (for  $V > kT/e$ ) for the value close to the more negative grain [24]. Once the position of the quasi-Fermi level at the grain boundary plane is established,  $\phi_B$  as a function of bias is determined. Using this expression, the density of the grain boundaries as a function of photon energy is given nearby. It shows that as grain boundaries in silicon is highest at the energy level of 0.55-0.56 eV. Thus, with photon energy between 0.47-0.67 eV, the current flowing through polycrystalline silicon is very low.

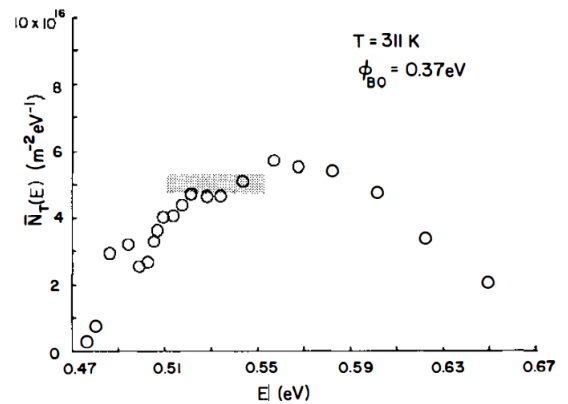


Figure 10: Density of grain boundaries vs photon energy

These boundaries obstruct the way of excited electrons. This, in effect, increases the overall resistance of the cell and as a result, the output current is low as compared to a single-crystal silicon cell, where there are no grain boundaries and there is an uninhibited flow of electrons. This overall decreases the efficiency of the polycrystalline solar cell.

### 5.3 Amorphous silicon:

Thin film solar cells are seen as competitor to the crystalline silicon due to their cost and efficiency tradeoff. However, there are several major aspects of amorphous silicon that requires further development: (a) a poor minority-carrier lifetime, (b) degradation of cell performance due to illumination, (c) difficulty in materials dopant and (d) poor-quality alloys.

“The disordered nature of amorphous silicon leads to a high density of states within the forbidden energy gap, in the form of band tail states and dangling bonds” [25]. Due to this, both the mobility and lifetime of free carriers are substantially reduced compared to those of crystalline materials. Furthermore, the absolute quantum efficiency, which is the percentage of photons hitting the photo reactive surface that will produce an electron-hole pair, decreases as the wavelength of light increases. The figure nearby represents the absolute quantum efficiency (QE) as a function of light wavelength. The shapes of the curves indicate that the quantum efficiency for wavelengths longer than 0.6  $\mu\text{m}$  is determined by the soft absorption edge of the i-layer. For shorter wavelengths, the QE is decreasing as it is determined by the photon absorption in the p-layer, from which no carriers are collected. There is also no charge carrier flow for the wavelength higher than 0.8  $\mu\text{m}$ .

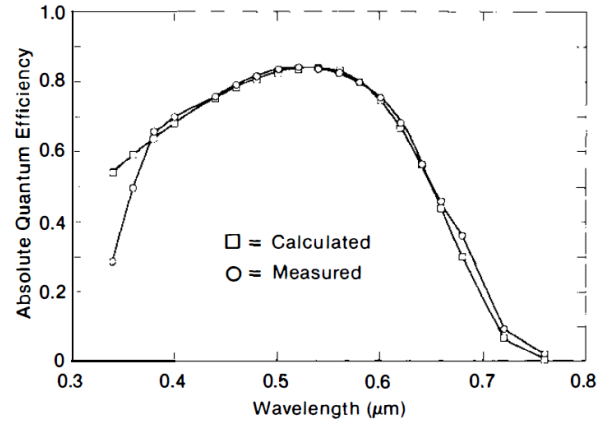


Figure 12: Absolute QE as a function of wavelength

## 6. Coping with the challenges:

Although, crystalline solar cells are used widely in the market today, issues associated with silicon are preventing the demand of the solar energy to increase. Though single crystalline silicon is very efficient relative to other kinds of the solar cells, the cost factor overrules its advantage with the efficiency. For polycrystalline silicon, the reduction in cost during the manufacturing stages by simple cooling of molten silicon makes it less efficient. Though, thin film is seen as competitor to the monocrystalline cell, development is still required for the issues related to poor minority carrier and lower quantum efficiency in amorphous silicon. Thus, in order to use the photovoltaic effect to its highest potential, it is important to find either the solution to the problems associated with silicon or other materials which can implement the photovoltaic effect in exclusive and cheaper ways.

### 6.1 Alternative methods:

There is still a lot of research is being done in terms improving the quality of silicon by overcoming the challenges. However, it is hard to find accessible solutions for the problems related to the characteristics of the material itself, such as absorption problem, grain boundaries. Because, it involves very complex methods in order to alter natural properties of the materials. Therefore, most of the research is based on changing the process of building the solar cells. Below are some suggestions provided:

In order to decrease the cost of sing crystalline cell production, there are many suggestions provided to modify the Czochralski method. The general approach is to reduce the amount of Si material used in wafer-Si cells. This can be realized by reducing the thickness of the Si wafer and reducing the material loss during ingot slicing. Furthermore, more approaches include directional solidification for

growth of poly-Si ingots, which requires ~12 kWh/kg of electricity versus ~100 kWh/kg for the Czochralski process [26]. Another example is screen printing for metallization, which prints Al and Ag pastes into various shapes for electrical contacts. In this method, thick film technology is used, which lends itself much more to automation than the conventional vacuum evaporation [27]. It is easy to fully automate, so it gives a cost reduction of the processing of 60% to 80%. Though there are a lot of other suggestions, one of the issues with them is that they are not efficient compared to the Czochralski method. Therefore, scientists are still searching options with cost reduction as well as efficiency.

In order to combat the recombinational losses, it is suggested to infuse a thick concentration of holes or atoms with vacant orbitals in the bottom layer of the cell [28]. This will ensure that the holes formed by the photons diffuse towards the upper layers and do not recombine with the electrons produced by the excitation of photons. However, it is quietly costly to implement this method for larger production.

One of the issues related to the general solar cell is the reflection loss, which can be calculated as:

$R(\lambda)\phi(\lambda)\exp^{-\alpha(\lambda)x}$ , where  $R(\lambda)$  is reflectivity of silicon,  $\phi(\lambda)$  is the photon incident on the surface and

$a(\lambda)$  is the absorption coefficient of silicon. Along with these factors, reflection also depends on the glass and anti-reflective coating used in the panel as shown in the figure nearby [29]. This shows that reflection loss can be controlled with use of appropriate glass and antireflective material. For decreasing the reflectance of the surface of the crystalline silicon cells, newer antireflective materials are being considered. One of them is silicon nitride, which promises a lower reflectance. Also, for decreasing reflectance, another recent development is etching of the surface of the silicon cell in order to give it an irregular dented surface [30]. This is done by using a solution of sodium hydroxide or potassium hydroxide (10-30% concentration) to acidify and corrode the surface.

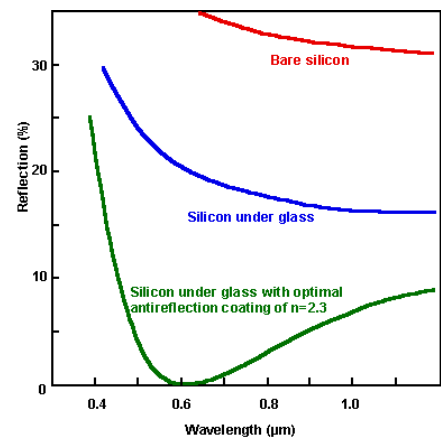


Figure 13: Reflection of solar panel under different conditions

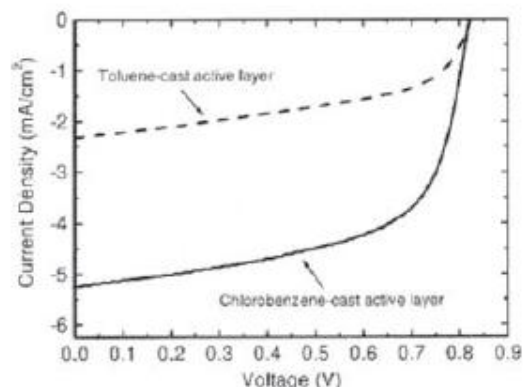
## 6.2 Alternatives for silicon

Along with the change in manufacturing method, alternatives for silicon are also being considered. Material like Gallium Arsenic (GaAs), Cadmium Telluride (CdTe), Copper-Indium:Diselenide (CIS) and Copper-Indium:Gallium-Diselenide (CIGS) is also being considered as the replacement for silicon in the solar cells. Among all of them, CIS and CIGS are also useful due to the remarkably high efficiency for polycrystalline thin films, at 18.8% in the laboratory, because of a band gap of 1.1-1.2 eV [31]. However, they are unstable and unreliable in conservable heat and humanity. Furthermore, there are problems with the availability and price of Indium. CdTe is also considered due its high optical absorption and variety of deposition techniques (e.g. close-spaced vapor transport, electro-deposition, and screen printing) producing a variety of junction structures [32]. However, problem associated with CdTe is its difficulty in controlling the doping and achieving stable, low resistance contacts to p-type CdTe. The biggest problem of this cell is its disposal due to use of hazardous Cd.

Along with these materials, research has been developing for the use of organic and non-crystalline particles in the photovoltaic cells. Organic photovoltaic cell (OPV) have become highly popular in last decade [33]. OPV cells contain at least one organic semiconductor or molecule under the effect of active light absorbing layer. The different kinds of sells produced under this technique include

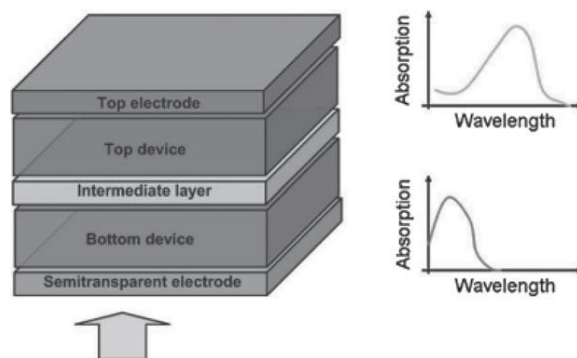
solid-state dye-sensitized cell and hybrid solar cells, which is produced by either dispersing inorganic nanoparticles into a semiconducting polymer matrix or combining inorganic nanostructured semiconductor such as ZnO or TiO<sub>2</sub> with organic semiconductors. The development of the OPV cells started with the invention of bulk hetero-junction (BHJ), where donor and acceptor materials were mixed together to form the higher efficiency cells.

Among all of OPV cells, a lot of research has been being done throughout last decade on polymer/fullerene based solar cells [34]. During this process, a progress was made on the design of the side chains that control the physical properties of polymer semiconductors, such as PPV, which had a twofold impact. On one hand, chiral side chains prevented polymer–polymer aggregation, while on another hand, side chains improved the solubility of the polymers. Furthermore, it was also experienced that the use of chlorobenzene instead of toluene in the cell helped to increase the current flowing through the junction, as shown in the figure. Furthermore, the degree of interaction between the conjugated polymers was also increased, which helped to raise the efficiency. However, it was found there was a very high energy band in PPV, which initiated further research.



**Figure 14: I-V for active layer of toluene and chlorobenzene**

In response to the issue related to the PPV material, highest even current density in organic material was observed in poly-alkyl-thiophenes (P3HT) and Phenyl-C61-butyric acid methyl ester (PCBM) [35]. After working with P3HT/PCBM, the initial efficacy was recorded at 5%. This rise in efficiency was mainly due to the increase in regioregularity of P3HT and optimization of annealing temperature and interface losses. Different methods were generated to form the OPV cells, which will increase the efficiency along with the stability of the cell. However, several investigations of BHJs of P3HT/PCBM with a focus on thermal stability have shown a drastic drop in performance due to morphological changes. Among a lot of methods suggested, one the best way of approaching this problem has been by design of cross-linkable molecules/polymers that can ‘lock’ the morphology and thus hinder the extensive phase separation [36]. A lot of research still has been going on improving the quality of organic cells and the most recent interest has been in the method of tandem cell architecture [37]. The figure nearby represents the typical organic tandem cell comprising two distinct devices stacked on top of each other, each of which is based on a donor/acceptor composite. The light that is not absorbed in the first (bottom) device impinges on the second (top cell) which incorporates lower band gap materials. Different materials are being tested to find the ideal combination, which can provide highest efficiency possible.



**Figure: Schematic of the two-layered Tandem cell**

Though, organic materials, especially polymers have potential to be in the solar cell, there are still issues related to these materials. These include degradation mechanism due to the organic reaction, instability of the cell along with the correlation between the separations of the bound electron-hole



excitation. Therefore, there are still doubts about increase in the performance of organic materials in the photovoltaic cell and studies have been following to find ways to tackle these challenges.

Along with polymers, nano-particles have been seen as the future replacement of silicon because it is believed that the size and shape control in the nanotechnology will allow for the customization of band gap through absorption of light across the whole spectrum [38]. Fabrication at the nano-scale provides a remarkable increase in the precision and level of control that can be obtained over solar cell development. Furthermore, “the 3D confinement leads to greater impact ionization and results in multiple charge carrier creation from a single photon”. As much as 44% efficiency has been tested into the laboratory, which has given a boost for the further research in this area.

## **7. Conclusion**

Solar energy is currently dominated by the single-crystalline silicon cell, which occupy as much as 90% total photovoltaic cells. However, there are still a lot of issues related to wafer-Si solar cells such as high manufacturing cost, recombinational, reflection and absorption losses along with efficiency issues in multi-crystalline and amorphous silicon based cells due to their disordered nature. Though there are numerous suggestions to solve these issues, it is hard to implement them due to their negative effect on efficiency. To make solar energy a possibility for the masses, scientists and researchers everywhere are trying to come up with newer and more economical ways of generating energy through solar power, especially by using various kinds of materials. Amorphous silicon based thin films cell, organic material based fullerene cell along with the cells containing nanoparticles are seen as the future competitors of single crystalline silicon cell. This rapid growth of this innovative research in wide range of active material, polymers and electrode combinations has provided many options for improving performance. Even though their efficiency and durability still remain in question, they are slowly but surely paving the way for making solar energy a viable, sustainable and prime source of energy in today's and tomorrow's world.

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