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SOLAR CELLS: The Ultimate Renewable Resource – A Review

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Abstract—*With the growing energy demands, the need for technology which must be economically, environmentally, and socially compatible has also increased. Scientists and researchers are in struggle to utilize the solar energy. Energy delivered by sun to earth in one hour is equal to the energy consumed by the people in one year. In recent years solar cell technology has achieved tremendous growth as sustainable source of energy. The fabrication of solar cells has passed through a large number of improvement steps from one generation to another. Silicon based solar cells were the first developed. Further development in solar cells results in enhanced cell efficiency. The progress is basically hindered by the cost and efficiency. In order to choose the right solar cell for a specific geographic location, we are required to understand fundamental mechanisms and functions of several solar technologies that are widely studied. In this paper, we have reviewed the operation, structure, efficiency and models of the conventionally used solar cells along with progressive development in the solar cell research from one generation to other.*

1. INTRODUCTION

Since the last decade, the world is developing at a pace like never before. An important factor behind this evolution is the recent advancements in the field of the energy generation technology. With the growing energy demands, the need for technology which must be economically, environmentally, and socially compatible has also increased. The energy-generating technologies can be classified as conventional and nonconventional [1]. The conventional energy sources have been in use since a long time. These include petroleum, coal, wood, etc. These types of sources have proved to be very beneficial for the human race development but still they have many disadvantages. Most of them cause environmental pollution and also are costly as the energy is needed to be transmitted over long distances after conversion into electricity. On the other hand, there are nonconventional energy sources like wind, solar, and thermal energies. These are inexhaustible and environment friendly but still need to be developed more to be conventionally used. Solar energy is the most abundant and clean form of energies offering an answer to the increasing concern of global warming and greenhouse gases by fossil fuels. It is considered as a good option not only for bulk electricity production but also for off grid purposes. They are also helpful in avoiding the long-distance transmission costs [2]. Solar Energy is the most plentiful energy source for the earth. All wind, fossil fuel, hydro and biomass energy have their origins in sunlight. Solar Energy falls on the surface of the earth at a rate of 120 petawatts, (1 petawatt = 1015 watt). Since it is possible to calculate the potential the solar energy received from the sun in one day and can satisfy the whole world's demand for each renewable energy source based on today's technology, figure 1. Future advances in technology will lead to higher potential for each energy source. However, the worldwide demand for energy is expected to keep increasing at 5 percent each year [3]. Keeping in view the worldwide demand, it is the solar energy that can satisfy such a huge increasing demand.

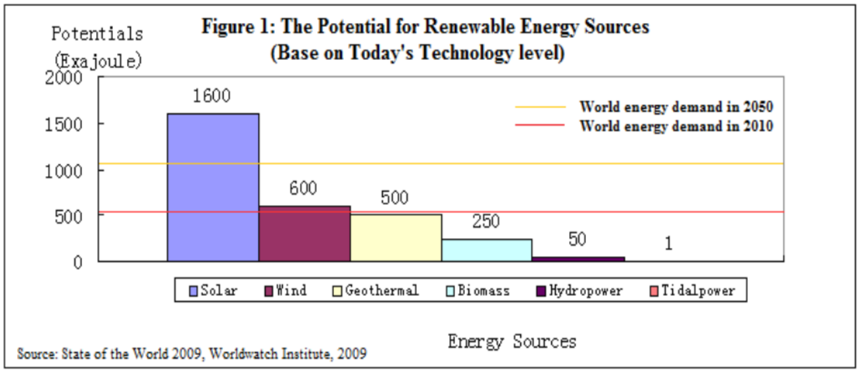

Figure 1. Potential for renewable energy sources

2. WHAT IS SUNLIGHT?

Sunlight is a form of "electromagnetic radiation". It is composed of waves of different lengths. The sun emits almost all wavelengths of light and the visible light that we see is a small subset of the electromagnetic spectrum shown in figure 2. Some of the wavelengths emitted by sun cannot be perceived with human eyes such as; radio waves, microwaves, infrared (IR), ultraviolet (UV), X-rays and gamma rays. The instrument used to simulate sunlight in a laboratory setting is called a solar simulator. A solar simulator has a light source that is designed to offer; similar intensity and spectral composition to that of natural sunlight.

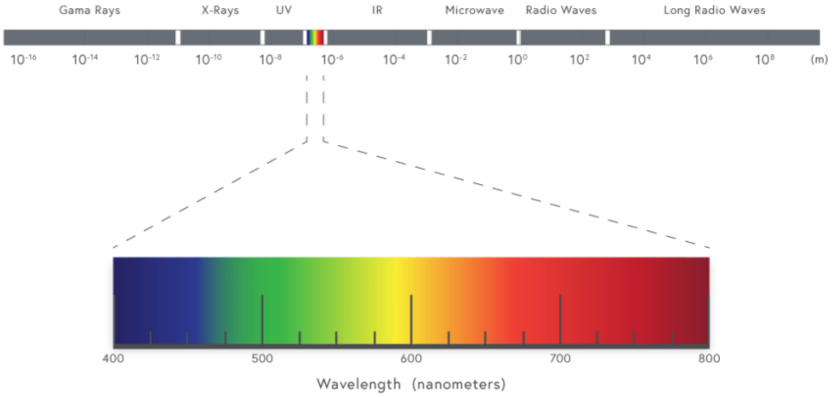

Figure 2: Electromagnetic Spectrum

Sun is a big spherical gaseous cloud composed of hydrogen nuclei. Within the inner core of the sun, nuclear fusion will take place, where four hydrogen atoms combine to form one helium atom with a lot of mass radiated as energy. Since mass of helium nucleus is less than that of the mass of four hydrogen atoms. This difference in mass is converted into energy. We can closely approximate the sun's surface temperature to be about 5800 Kelvin (K), or 5500 Celsius (C). So the sun's radiation spectrum matches a 5800 K blackbody.

3. ABSORPTION OF LIGHT

When the photons are incident on the surface of a semiconductor, depending on the energy of the photon, it can be either reflected from the top surface, will be absorbed in the material or, failing either of the above two processes, will be transmitted through the material. For photovoltaic devices, reflection and transmission are typically considered loss mechanisms as photons which are not absorbed do not generate power. If the photon is absorbed it has the possibility of exciting an electron from the valence band to the conduction band. A key factor in determining if a photon is absorbed or transmitted is the energy of the photon. Therefore, only if the photon has enough energy will the electron be excited into the conduction band from the valence band. Photons falling onto a semiconductor material can be divided into three groups based on their energy compared to that of the semiconductor band gap:

If $E_{ph} < E_{G,}$ photons will pass through (transparent). If $E_{ph} > E_{G,}$ photon is strongly absorbed. However, for photovoltaic applications, the photon energy greater than the band gap is wasted as electrons quickly thermalize back down to the conduction band edges. If $E_{ph} = E_{G,}$ photons are efficiently absorbed and hence electron-hole pair is generated. The absorption of photons results in the creation of both a majority and a minority carrier. In many photovoltaic applications, the number of light-generated carriers is of orders of magnitude less than the number of majority carriers already present in the solar cell due to doping. How far into a material, light of a particular wavelength can penetrate before it is absorbed is determined by absorption coefficient. In case of low absorption coefficient, light is only poorly absorbed, and if the material is thin enough, it will appear transparent to that wavelength. Materials with higher absorption coefficients more readily absorb photons, which excite electrons into the conduction band. Absorption coefficient depends on the material and also on the wavelength of light which is being absorbed.

4. SOLAR CELL OPERATIONAL FUNDAMENTALS

A simple solar cell is a *PN* junction diode. The schematic of the device is shown in figure 3 [4].

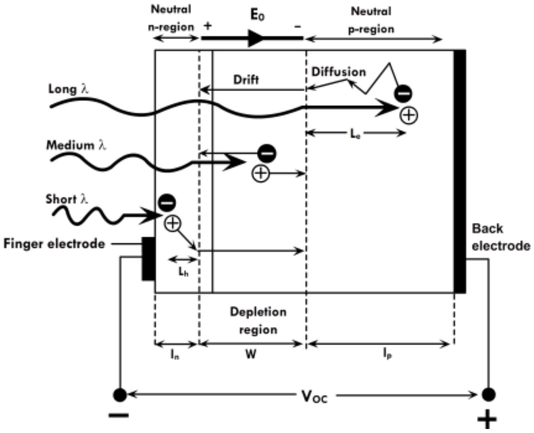

Figure 3: Principle of operation of a *pn* junction solar cell

The *N* region is heavily doped and thin so that the light can penetrate through it easily. The *P* region is lightly doped so that most of the depletion region lies in the *P* side. The penetration depends on the wavelength. Electron hole pairs (EHPs) are mainly created in the depletion region and due to the built-in potential and electric field, positive charge is separated from the negative charge physically, that will generate voltage. Once separated physically they will not move back. P side will become positive because of accumulation of holes and N side will become negative because of accumulation of electrons, figure 4. This is called as photovoltaic effect.

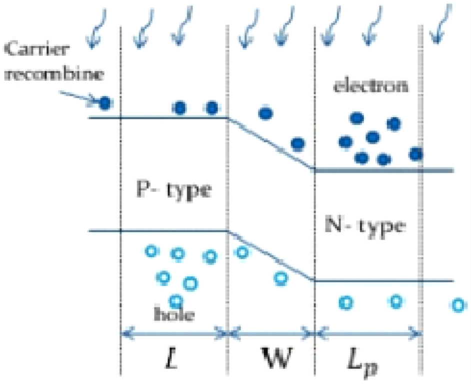

Figure 4: Junction under Illumination

When an external load is applied, the excess electrons travel through the load to recombine with the excess holes. Electrons and holes are also generated with the *P* and *N* regions, as seen from figure 3. The shorter wavelengths (higher absorption coefficient) are absorbed in the *N* region and the longer wavelengths are absorbed in the bulk of the *P* region. Some of the EHPs generated in these regions can also contribute to the current. Typically, these are EHPs that are generated within the minority carrier diffusion length, L_e for electrons in the *P* side and L_h for holes in the *N* side. Carriers produced in this region can also diffuse into the depletion region and contribute to the current. Thus, the total width of the region that contributes to the solar cell current is $w_d + L_e + L_h$, where w_d is the depletion width, figure 4.The carries are extracted by metal electrodes on either side. A finger electrode is used on the top to make the electrical contact, so that there is sufficient surface for the light to penetrate. Since we want maximum light to penetrate, so the width of the finger electrodes is kept small. Because of the light falling on PN junction, voltage is generated. This voltage can be used to drive the current.

5. SOLAR CELL I-V CHARACTERISTICS

Consider the simplest photovoltaic device and the mathematical description of the electrical properties of such a device. Here we use the simple equivalent circuit for a photovoltaic cell as shown in figure 5, including a current generator corresponding to photo excitation, a diode containing the internal electric field necessary for driving photoexcited carriers to the external circuit, a series resistance, R_s, and a parallel resistance, R_p. We make the model even simpler by considering at this point an "ideal device" with $R_s = 0$ and $R_p = \infty$. If we make the simple assumption that the current generated by light can simply be added to the current flowing in the dark, then the current density J flowing in the device in the presence of photo excitation can be expressed as:

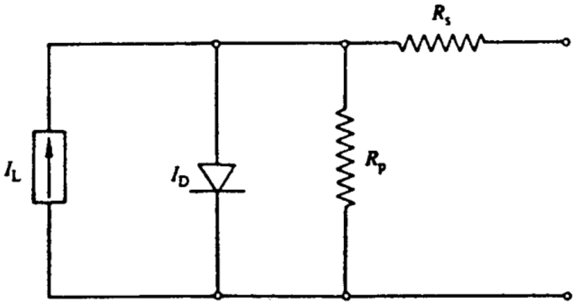

Figure 5: Equivalent Circuit of Photovoltaic Cell

$$J = J_L - J_0\left(e^{\frac{qV}{nkT}} - 1\right) \qquad \text{........ (1)}$$

Equation (1) does not take care of series and shunt resistance. The first term on the right of the above equation is the forward current driven by the voltage **V**, and the second term is the reverse current associated with photo excitation. J_0 is often called the "reverse saturation current" of the diode, the value of J in the dark for large negative values of **V** in ideal junctions, which depends on the actual transport mechanism for the diode current and **n** is the called as the "ideality factor" that has a value depending on the mechanism of the junction transport (e.g. n = 1 if the transport process is diffusion, n = 2 if the transport process is recombination in the depletion region) [5]. Typical variations of total current I in both the dark and the light as a function of are given in figure 6. If the voltage is zero (short-circuit condition), then of course there is zero current in the dark, but in the light we have

$$J_{SC} = J_L \qquad \text{........ (2)}$$

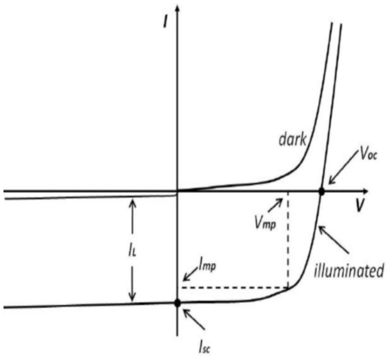

Figure 6: VI Characteristics (Dark and Light)

Short-circuit current is controlled only by the photo induced current generation and the recombination processes. Under open circuit condition i.e. when total current is zero, then solution of equation 1 is given as:

$$V_{OC} = \frac{nkT}{q} \ln\left(\frac{J_L}{J_0} + 1\right) \qquad \text{……… (3)}$$

Thus the open-circuit voltage is controlled by the current generation and recombination processes. Combining equations 2 and 3 shows that the relation between J_{sc} and $V_{\grave{o}c}$ is given by

$$J_{SC} = J_0\left(exp\left(\frac{qV_{OC}}{nkT}\right) - 1\right) \qquad \text{……… (4)}$$

Equation (4) is exactly similar to equation (1) for J versus V in the dark for this ideal junction device.

6. SOLAR CELL MODELS

Use of lumped circuit model is a convenient and widely used method for simulating solar cell performance. There are two main lumped circuit models in use: single diode model, figure 5 and two diode model or double diode model, figure 7.

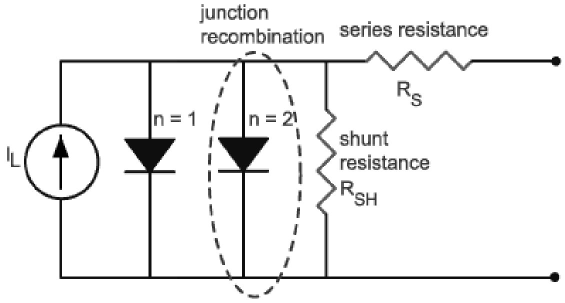

Figure 7: Two Diode Model

The first one is described by the modified Shockley diode equation incorporating a diode quality factor. Analytical expressions for the rapid extraction of parameters for this model were recently reported [6]. The second model i.e. two diode model is more accurate than the single diode model [7]. Here one more diode is included to provide more accurate VI characteristics. This model simulates the space-charge recombination effect by incorporating a separate current component with its own exponential voltage dependence. These circuit models are based on assumptions that may not always be valid. The main assumption is that of linearity, namely that the current flowing through the cell is a superposition of two currents, one due to junction bias and the other due to illumination [8]. This main assumption is made possible by other simplifying assumptions. The current-voltage relationship in case of single diode model is given as:

$$\left(J = J_L - J_0\left(e^{\frac{q(V+IR_S)}{nkT}} - 1\right) - \left(\frac{V+IR_S}{R_{sh}}\right)\right) \qquad \text{……… (5)}$$

We know that in solar cells charge recombination will take place wherein EHP recombines before the electron has managed to make way around the circuit through the load. This recombination occurs at the edges and the surfaces of the device where the charge carriers are not under the influence of the junction potential. The physics driving how quickly and when the recombination occurs are fairly complex, but the end result is that the recombination current has an exponential dependence on voltage. This is considered to be same as having another diode through which the current leaks. So this additional diode needs to be added to the circuit model, figure 7. The first diode is a result of solar cell being a semiconductor, whereas the second diode is a result of recombination. This diode can be added to the circuit model as another path for current to leak out before reaching our load. Resulting equation is given below:

$$J = J_L - J_{01}\left(e^{\frac{q(V+IR_S)}{nkT}} - 1\right) - J_{02}\left(e^{\frac{q(V+IR_S)}{2nkT}} - 1\right) - \left(\frac{V+IR_S}{R_{sh}}\right) \qquad \text{…… (6)}$$

Where J_{01} is the reverse saturation current due to diffusion, J_{02} is the reverse saturation current due to recombination in the space charge layer.

7. EFFECT OF R_S AND R_{SH} ON VI CHARACTERISTICS

The series resistance has the effect of moving the “cliff” of the diode curve to a lower voltage, as shown in figure 8, which ultimately lowers the maximum power we can get out of a solar cell. Near the open-circuit voltage, the IV curve is strongly affected by the series resistance.

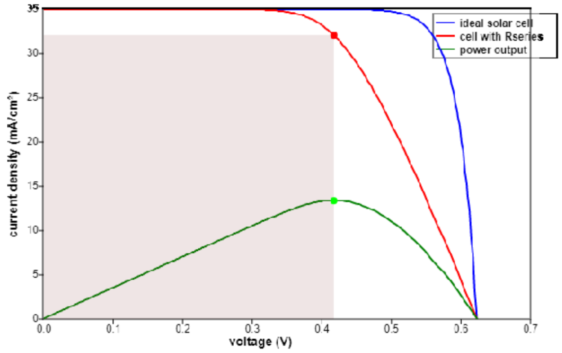

Figure 8: Effect of series resistance on VI characteristics

The doping of semiconductors into p-type or n-type is never quite perfect, and therefore there are defects in a given solar cell. These defects can provide alternate paths that electrons can travel through instead of desired load. When current takes a shortcut to the end instead of going through the desired wire, this is called a short circuit. Another word for short-circuit is a shunt, so this effect is often represented as a shunt resistance in the circuit model. This resistance is always connected in parallel with the load, so it is sometimes also called a parallel resistance. A shunt resistance has the effect of steadily decreasing the current as the voltage is increased as shown in figure 9. A lower shunt resistance means there are more defects and leakage currents, which reduce the maximum power we can get out of our solar cell.

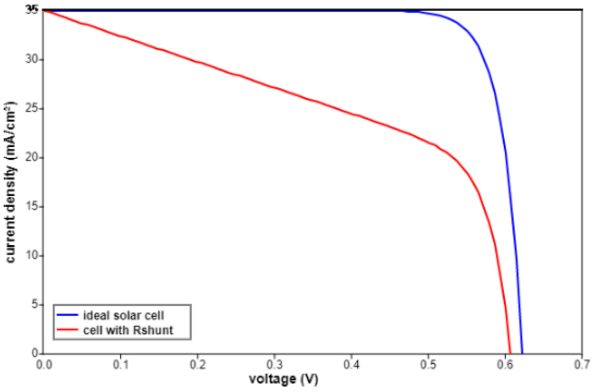

Figure 9: Effect of shunt resistance on VI characteristics

8. CLASSIFICATION OF SOLAR CELLS

The modern photovoltaic technology is based on the principle of electron hole creation in each cell composed of two different layers of p-type and n-type materials of a semiconductor material. The various types of materials applied for photovoltaic solar cells includes mainly in the form of silicon (single crystal, multi-crystalline, amorphous silicon) [9][10], cadmium-telluride [5] [9], copper-indium-gallium-selenide [5] [9] [11], and copper-indium-gallium-sulfide [12] [13]. On the basis of these materials, the photovoltaic solar cells are categorized into various classes shown in figure 10.

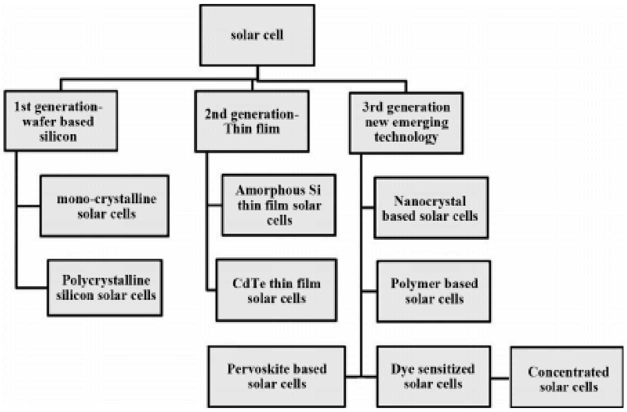

Figure 10: Classification of Solar Cells

8.1 First Generation Solar Cells

Although Shockley and Queisser have proposed that the maximum theoretical solar conversion efficiency that can be achieved for a single pn junction PV cell is at a band gap of 1.34 eV. At present, silicon with a band gap of 1.1 eV is used in nearly 90% of all solar cell semiconductors. Silicon is the second most abundant element present on earth and its nontoxic nature makes it suitable for the widespread use in the PV industry [14].The silicon based solar cells a classified into two subgroups:

i) Single/ Mono-crystalline silicon solar cells
ii) Poly/Multi-crystalline silicon solar cell

Mono crystalline solar cell is manufactured from single crystals of silicon by a process called Czochralski process [15]-[17]. During the manufacturing process, Si crystals are sliced from the big sized ingots. These large single crystal productions require precise processing; such solar cells are more expensive. The efficiency of mono-crystalline single-crystalline silicon solar cells lies between 17% - 18% [11]

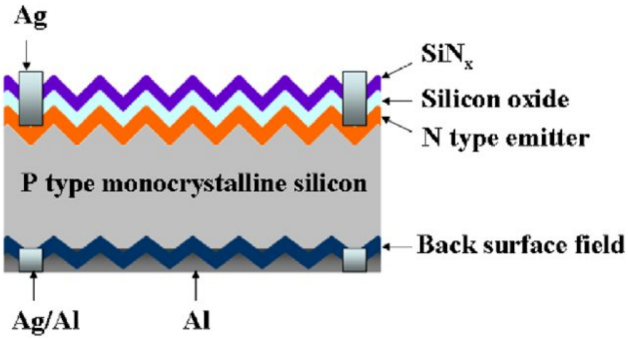

Figure 11: Monocrystalline silicon solar cell sample structure.

Polycrystalline solar cells are generally composed of a number of different crystals, coupled to one another in a single cell. Fabrication cost of polycrystalline Si solar cells is less than the mono-crystalline solar cells. They are believed to occupy most up to 48% of the solar cell production worldwide during 2008 [18]. During solidification of the molten silicon, various crystal structures are formed. Though they are slightly cheaper to fabricate compared to monocrystalline silicon solar panels, yet are less efficient ~12% - 14% [19]. Efficiency of the crystalline Si (c-Si) solar cells could be increased (upto 24.7%) by improving optical design and electrical design. Electrical improvements include improved passivation of surface regions and optimal contact technology. Optical improvements can be made by reduced reflection and improved light trapping within the cell.

8.2 Second Generation Solar Cells

Most of the thin film solar cells and amorphous silicon (a-Si) are second generation solar cells. Thin-film technology extensively reduces amount of semiconductor material used and hence reduces the production costs. Silicon-wafer cells have light absorbing layers up to 350 µm thick, while thin-film solar cells have a very thin light absorbing layer, generally of the order of 1 µm thickness [20]. But due to high radiation capture losses, its efficiency is lower than c-Si cells [21].Thin film solar cells are classified as;

i) a-Si (Amorphous Silicon)
ii) CdTe (Cadmium Telluride)
iii) CIGS (Copper Indium Gallium di-Selenide)

Amorphous silicon is silicon that lacks a crystalline structure, which is used to develop a thin film solar cell and is usually found in smaller solar panels such as those used to power private homes or in calculators. These substrates require a smaller amount of energy for processing [22]. Therefore, a-Si amorphous solar cell is comparatively cheaper and widely available. The main issue of a-Si solar cell is the poor and almost unstable efficiency. The cell efficiency automatically falls at PV module level. Currently, the efficiencies of commercial PV modules vary in the range of 4% - 8%. They can be easily operated at elevated temperatures, and are suitable for the changing climatic conditions where sun shines for few hours [23].

Cadmium Telluride: Photovoltaic solar cells based on CdTe contribute to the major part (about 5.1%) of commercial thin-film module production worldwide. The United States is the leading manufacturer of CdTe PV. In addition to high efficiency, these cells can be quickly manufactured and also costs low [24].CdTe has a band gap of ~1.5 eV as well as high optical absorption coefficient and chemical stability. These properties make CdTe most attractive material for designing of thin-film solar cells. CdTe is an excellent direct band gap crystalline compound semiconductor which makes the absorption of light easier and improves the efficiency. However, there are certain environmental issues with cadmium component of solar cell. Cadmium is regarded as a heavy metal and potential toxic agent that can accumulate in human bodies, animals and plants. The disposal of the toxic Cd based materials as well as their recycling can be highly expensive and damaging too to our environment and society

Copper Indium Gallium Di-Selenide (CIGS) Solar Cells: CIGS is a quaternary compound semiconductor comprising of the four elements, namely: Copper, Indium, Gallium and Selenium [25]. CIGS are also direct band gap type semiconductors. Compared to the CdTe thin film solar cell, CIGS hold a higher efficiency ~10% - 12%. Due to their significantly high efficiency and economy, CIGS based solar cell technology forms one of the most likely thin film technologies.

8.3 Third Generation Solar Cells

The categories of third-generation solar cells include:

1) Nano crystal based solar cells.
2) Organic (Polymer) solar cells
3) Dye sensitized solar cells.
4) Concentrated solar cells

One of the fundamental actors going for third generation solar cells is that they offer very high possibilities for improving parameters such as charge generation, separation, molecular mass, band gap (determining the ability to harvest light efficiently in different parts of the solar spectrum, especially the infrared), molecular energy levels, rigidity, and molecule-to-molecule interactions. They are also extremely lightweight and flexible making them easy to work with and combine with other molecules. Traditional solar cells have had several major drawbacks that need to be worked upon to constantly overcome barriers for high performance. Low efficiency and high cost are the foremost factors that are needed to be overcome for a much more robust technology to be in place. Also, the key ingredient, refined silicon, has become more expensive, which makes it difficult to reduce the cost of the solar cells. Silicon also has many physical barriers, which limit the efficiency and use of traditional solar cells. Nanotechnologists and other University innovators are developing newer solar cells that are less expensive, flexible, compact, light weight, and efficient. They are able to do this by finding alternative chemicals and materials to harness solar energy. Third generation cells are the new promising technologies but are not commercially investigated in detail.

These solar cells are targeted to achieve both high efficiency and low cost. These devices can be fabricated with high throughput printing techniques that consume less energy and require less capital investment than silicon-based devices and other thin-film technologies. These solar cells that are potentially able to overcome the Shockley–Queisser limit of 31–41% power efficiency for single band gap solar cells [26]. Third-generation solar cells are solution processable solar cells with excellent potential for large-scale solar electricity generation.

9. CONCLUSION

In this paper various concepts of solar cell have been presented. Different models that are used to represent the solar cells have been discussed along with the effect of shunt and series resistance on VI characteristics of the solar cells. Various state-of-the-art solar photovoltaic materials have been discussed in this paper. The first half of the paper is mainly focused on the operation, structure, efficiency, and models of the conventionally used solar cells. Si-based solar cells still rule the PV industry. Many emerging technologies have been discussed in the later sections of the paper. The environmental friendly revolution can be made by evolution in photo voltaic technology.

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