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WHICH SOLAR CELL WILL PROVE TO BE A SUSTAINABLE FUTURE ASSET? : A COMPLETE REVIEW

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ABSTRACT

The use of Solar cells is becoming popular and by the end next few decades the chances of running out of the natural resources present on the earth are very likely. Therefore, many alternatives are being searched and developed; one of them being the Solar cells that were first developed in 1954. Ever since then, there have been many advances in the same. In this paper, the different categories of solar cells have been studied from the core and the respective efficiencies have been thoroughly compared to conclude the types of solar cell that are going to prove to be the most efficient and open to advancement in the near future.

Keywords- Solar cells, Generations of solar cells, Development and efficiencies

1. Introduction

The first-generation solar cells grown on silicon wafers are the oldest and the most popular due to their high-power efficiencies. Next comes, thin films based second generation of solar cells which are more economical and have a very thin light absorbing layers in comparison to the first-generation solar cells. High efficiency third generation solar cells include Quantum dots, Polymer and Dye sensitized solar cells. Organic solar cells use carbon material as a semiconductor and are also referred as “plastic solar cells”. Organic solar cells are light weight and can fit anywhere easily but have short lifespan in comparison to inorganic solar cells. Presently, they are not available in the market and researchers are still investigating them. Inorganic solar cells comprise crystalline, amorphous, and microcrystalline material i.e., silicon to produce electricity. These cells are also called as traditional solar cells, usually installed on top of the roof.They are more efficient than organic solar cells.

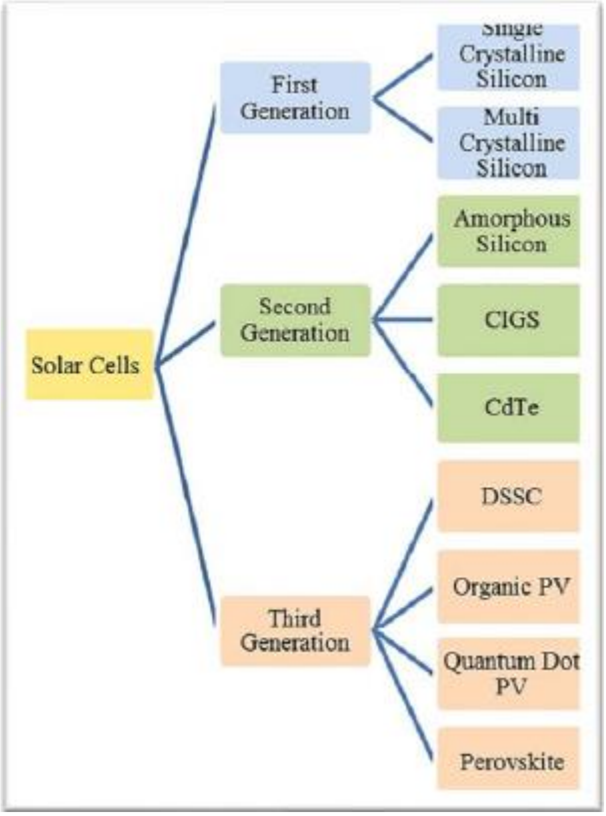


Fig. 1: Generations of Solar cells

2. First Generation

2.1 Silicon wafers

Solar cells produced on the silicon wafer are the first-generation solar cell. They cover 80% of the solar market and currently are the oldest and most popular technology available for the residential use due to its high-power efficiencies and longer lasting.

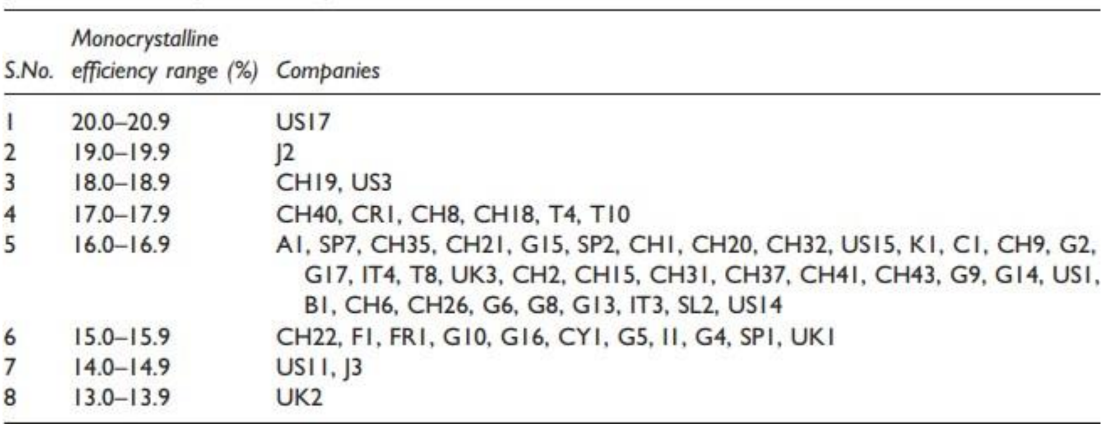
The silicon wafer-based technology can bedivided into two categories:

- Single/Mono crystalline silicon solar cell
- Poly/Multi crystalline silicon solar cell

2.2 Mono crystalline silicon solar cell

The cells are sliced from large crystals grown under controlled conditions during the manufacturing process. Since it is hard to develop large crystals of pure silicon in mono crystalline solar cells, the production cost of this type of panel has traditionally been the largest of all solar panel varieties. The second problem with monocrystalline silicon panels is that they lose productivity when the temperature rises past 25° Celsius, so they can be mounted in such a manner that air will circulate over and under them to maximise performance. Monocrystalline materials are commonly used because they have a higher performance ratio than multicrystalline materials. Table 1 represents efficiencies of monocrystalline silicon modules of 60 companies.

Table 1: Efficiency of Mono crystalline PV Modules



S.No.	Monocrystalline efficiency range (%)	Companies
1	20.0–20.9	US17
2	19.0–19.9	J2
3	18.0–18.9	CH19, US3
4	17.0–17.9	CH40, CR1, CH8, CH18, T4, T10
5	16.0–16.9	A1, SP7, CH35, CH21, G15, SP2, CH1, CH20, CH32, US15, K1, C1, CH9, G2, G17, IT4, T8, UK3, CH2, CH15, CH31, CH37, CH41, CH43, G9, G14, US1, B1, CH6, CH26, G6, G8, G13, IT3, SL2, US14
6	15.0–15.9	CH22, F1, FR1, G10, G16, CY1, G5, I1, G4, SP1, UK1
7	14.0–14.9	US11, J3
8	13.0–13.9	UK2

2.3 Development and Efficiency of Single-crystalline solar cells

Single-crystalline GaAs- A single crystalline GaAs-based solar cell has the largest Photocurrent Efficiency (PCE) (29.1%) of any single-junction cell. Because of the lift-off mechanism, highly reflective back contacts may be used instead of substrates that add parasitic absorbance. The absorber material's near- unity photoluminescence quantum yield (PLQY) (99.7%), the suppression of non- radiative recombination at the charge- collecting interfaces, and the highly reflective back interaction all assist in photon recycling until they leave the cell from the front surface. All of these aspects combine to give the cell a near- unity (external radiative efficiency) value of 12.

Single-crystalline InP- The champion cell, which is built on single-crystalline InP, now has a PCE of 24.2 %, up from 22.1 % previously. The high–low doping scheme used in the emitter layer (which is the most heavily doped layer, and whose function is to inject and/or emit the carrier into a less doped base layer) is responsible for the increase in photocurrent performance. Despite the advancements, this technology's operational loss and photocurrent performance remain well below their theoretical limits. With materials properties similar to GaAs and GaInP and Eg PV =

1.38 eV, we expect this technology's efficiency to approach that of GaAs in the coming years, assuming the problems of interfacial recombination and parasitic absorbance can be overcome.

Single-crystalline Si-

The highest PCE of a c-Si solar cell was 25% for almost 14 years. The passivated emitter and rear locally diffused (PERL) solar cell technology were used in this c-Si solar cell, which had a 4cm2 surface area. However, due to shadowing from the front grid and non-radiative surface recombination caused by the contacts, this cell suffered photocurrent losses. The current champion c-Si cell has a PCE of 26.7 % (with a surface area of 79 cm2). It was made possible by advances in processing technology and ongoing materials production for the microelectronics industry in order to obtain high-grade electronic quality Si crystals. The question now is whether new technological advancements will help c-Si technology become even more effective. There is still room for improvement, especially in terms of current performance, in our opinion.

2.4 Poly crystalline silicon solar cell

A polycrystalline module is made up of a variety of different crystals that are linked together in a single cell. Since tightly regulated growth conditions are not needed, producing silicon wafers in moulds from multiple crystals is less expensive than producing single crystal silicon wafers. Polycrystalline silicon-based solar cells are made by cooling a graphite mould filled with molten silicon. Though Polycrystalline silicon solar panels are less expensive per unit area than mono crystalline panels, but they have a lower quality.

2.5 Development and Efficiency of Polycrystalline Solar Cells

Polycrystalline Si- This champion mc-Si cell's photocurrent performance is comparable to c-Si cells and superior to technologies based on other polycrystalline materials. However, the operational loss is higher than with single-crystal-based technologies, as predicted. Zhao et al. (1998) recorded honeycomb textured solar cells with a multi-crystalline efficiency of 19.8 %. Since multi-crystalline solar modules are less expensive to produce, theyare more common on the market. However, when compared to monocrystalline solar modules, they are less powerful. Neo Solar Power Corporation from Taiwan has the highest commercial module efficiency of 16.9%, while monocrystalline has a maximum efficiency of 20.4 %. As a result, efforts are being made to make multi- crystalline technology compatible with monocrystalline technology (Becker et al., 2011).

3. Second Generation

3.1 Thin film Technology

Thin film is an alternative technology, which uses less or no silicon in the manufacturing process. While wafer technology is capable of meeting the high efficiency goal, thin film can satisfy minimum material usage as well. Both goals need to be met simultaneously to enable the production of electricity at a lowcost and allow high market penetration of solar electricity. **α-Si, CdTe and CIGS** arethe three most widely commercialized thin film solar cells. Common among the three materials is their direct band gap, which enables the use of very thin material. They also have a very low temperature coefficient; however, in contrast, wafer technologies and their performance are notimpeded by low light intensity. Additionally, all the three technologies canbe incorporated into building integrated photovoltaics (BIPV). The amorphous silicon solar cell finds its use mainly in consumer electronics such as calculators, watches, etc. The absorption coefficient of thin film materials is much lower than that of its crystalline counterparts. When compared to CdTe and CIGS, α-Si not onlyrequires a lower amount of silicon, but is also less toxic. CdTe's usage of cadmium proves to be harmful to both the producer and the consumer, slightly limiting its commercial applications. Throughout history, α-Si has had the longest time in the commercial arena, starting with its introduction as a reliable power source of watches, clocks, and calculators in the late 1980s. However, CIGS and CdTe are relatively new technologies, and are more promising in terms of energy conversion efficiency than α-Si. Despite thisadvantage, CIGS and CdTe technologiesstill lag behind crystalline silicon solar cell counterparts in efficiency and reliability.

3.2 Amorphous silicon (α-Si)- Amorphoussilicon is the most commonly developed and a non-crystalline allotropic form of silicon. It is most popular among thin film technology but it is prone to degradation. The word “Amorphous Silicon” means a non- crystalline structure, lacks a definite arrangement of atoms. As compared to traditional silicon methods, silicon is deposited as very thin layer on backside of substrate. The manufacturing method is lessenergy intensive yet complex than crystalline panel. The issue of amorphous silicon is that they are much less efficient per unit area (upto 10%). They are suitablefor conditions where sun shines for fewhours as they can easily operate at low lightlevels Some of the varieties of α-Si areamorphous silicon carbide (α-SiC), amorphous silicon germanium (α-SiGe), microcrystalline silicon (α-Si) and amorphous silicon-nitride (α-SiN) (Parida et al., 2011). Due to random structure, α-Sihas a high band gap of 1.7 eV (Boutchich etal., 2012) and hence, compared tomonocrystalline silicon, it has 40 times higher rate of light absorptivity (Mah, 1998). The optical absorption spectrum of hydrogenated α-Si: H is transparent up to1.7 eV and is highly absorptive starting at 2eV. These initial properties have led to a wide spread interest in α-Si in solar industry and research institutes. Additional benefits of α-Si: H include low manufacturing cost, and a shorter energy payback time. It also holds the first position in current market amongst all thin film materials.

3.3 Efficiency of α-Si

The first amorphous thin film solar cell of 1mm thick was reported with an efficiency of 2.4% by Carlson and Wronski (1976). Inaddition, further improvements andpotential of thin film solar cell is detailed byRech and Wagner (1999). Over the past decade, there has been almost no progress in the PV technology of a-Si, at least as far as the conversion efficiency is concerned. Presumably, this lack of progress is due, atleast partly, to the intrinsic material limitations of the a-Si absorber (owing to itsstatic disorder). This technology has thehighest operational loss among all those we consider here. Approximately 35 years ago, it was shown that the presence of tail states in an amorphous semiconductor, such as a- Si, leads to several hundreds of millivolts of additional voltage loss in the system. We argue that this intrinsic voltage loss (also observed in CZTSS and CZTS) is a bigger obstacle for market penetration than the much-studied initial intrinsic instability of the material, the so-called Staebler– Wronski effect. We do note, however, that a-Si is important for achieving high- efficiency c-Si SHJ cells, and although a-Si does not have the central role of absorber, the past developments in a-Si have enabled the present world-record c-Si efficiency, and thus, a-Si is a good example of cross- fertilization between PV technologies.

3.4 CIGS- Copper Indium Gallium Selenide is an advanced research material in which Gallium is added tocopper indium (Di) selenide (Schock and Shah, 1997). The direct band gap of these periodic table group I III VI elements varies from 1 ev to 1.7 ev [CuInxGa(1-x) Se2]. In comparison to other semiconductor materials, the CIGS material requires a thin layer because it has a high absorption coefficient of more than 10 power 15/cm for 1.5ev and higher energy photons and strongly absorbs sunlight. In 1976, Kazmerski et al. developed the first thin- film CIGS solar cell with a 4.5 % conversion efficiency. The CIGS isdepicted in the diagram below, with soda lime glass serving as the substrate.

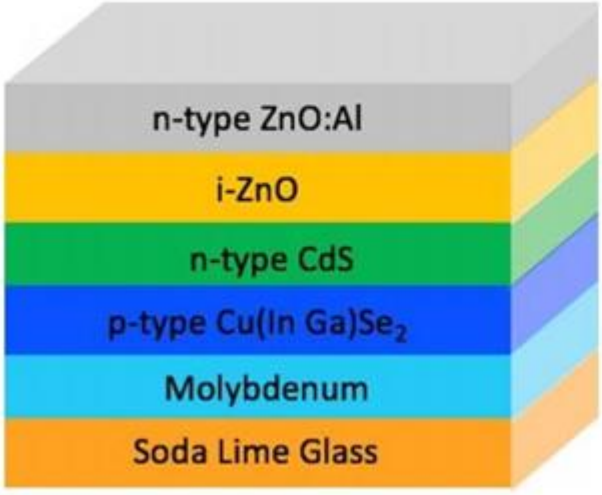


Fig 2: Structure of CIGS

The molybdenum on top of the glass makes contact with the p-type Cu (InGa) Se2. The main junction is formed by p-type Cu (InGa)Se2 with the n-type CdS which acts as the buffer layer. On top of the CdS, an intrinsic zinc oxide layer is present, and then-type ZnO:Al layer serves as the front contact. The semiconductor used in this solar cell has a thickness of 1.2– 4.04 m, which is very thin when compared to crystalline silicon, which has a thickness of170– 200 m.

3.5 Efficiency of CIGS

Due to their high efficiencies and low cost, CIGS-based solar cells are likely to be the most popular thin film technology. Solar cells made of CIGS are more stable and have a higher conversion efficiency than other types of cells. In 2013, scientists at the Swiss Federal Laboratories for Material Science and Technology achieved a 20.4% efficiency on flexible polymer foils.NREL has attained a 21.7% efficiency ratetill date.

3.6 CdTe- Cadmium telluride (CdTe) is one of the most important types of thin film solar cells in terms of cost and feasibility (Bertolli, 2008; Goswami and Kreith, 2007). Between layers of cadmium sulphide, a p-n junction diode is formed. The following is the manufacturing process: first, CdTe-based solar cells are synthesised from polycrystalline materials, with glass as the substrate. Second, deposition is carried out, in which several layers of CdTe solar cells are coated on to the substrate using various cost-effective methods. However, because of the poisonous nature of cadmium, which can accumulate in human bodies, animals, and plants, it causes a slew of environmental issues. More hazardous Cd recycling and disposal is also harmful to the atmosphere (Bagher et al., 2015). All thin film solar cells can use CdTe as a primary material. It's a direct band gap substance with a high absorption coefficient, similar to CIGS, and it's a stable compound that can be made in a number of ways. If both bulk and surface recombination are regulated, a thin film of CdTe is adequate for producing highefficiency cells.

3.7 Efficiency of CdTe

Britt and Ferekides (1993), Aramoto et al. (1997), and Wu et al. (2001) reported that CdTe solar cells have a cell efficiency of 15 to 16%. The company First Solar (2011) achieved a CdTe solar cell efficiency of 17.3%, which was verified by NREL. With estimated efficiencies of 18.7%, 19.6%, 20.4 %, and 21%, First Solar Research and Development has dominated the past decade, with a heavier focus on commercialization. First Solar creates a full solar module using a continuous manufacturing process.

4. Third Generation

4.1 Dye-Sensitized Solar Cells (DSSC)- Since O'Regan and Grätzell recorded the fabrication of DSSC in 1991, it has become a promising energy generating device, with efficiencies of 7-8%. The DSSC is easy to make, inexpensive, and has a high power- to-conversion performance. These characteristics pique the interest of scientists and researchers. A dye-sensitized transparent conducting substrate, semiconductor film (such as titanium dioxide (TiO_2), zinc oxide (ZnO), tin dioxide (SnO_2), Niobium pentoxide ($Nb2O_5$)), electrolyte, and counter electrode are all components of an ideal DSSC (CE). The core of the DSSC is a mesoporous oxide film containing TiO_2 nanoparticles as a roadway for electrons to cross from the cathode to the anode; the particles' diameters range between 10 and 30 nm, and the film's thickness is about 10 m, and it is doped with a dye to absorb photons. The TiO_2 layer is deposited on a glass substrate that has been coated with transparent conducting oxide (TCO) or fluorine-doped tin oxide (FTO). The dye oxidises the dye by removing electrons from photons and transferring them to the conduction band. The iodide/triiodide redox mechanism is how the dye recovers the missing electrons from the electrolyte. The I- loses electrons to the dye, resulting in the formation of $3I_3$ triiodide. The Triiodide gains an electron from the cathode, which is coated in platinum as a catalyst, and then the electrons migrate from the semiconductor side to the counterelectrode side, creating a current flow.

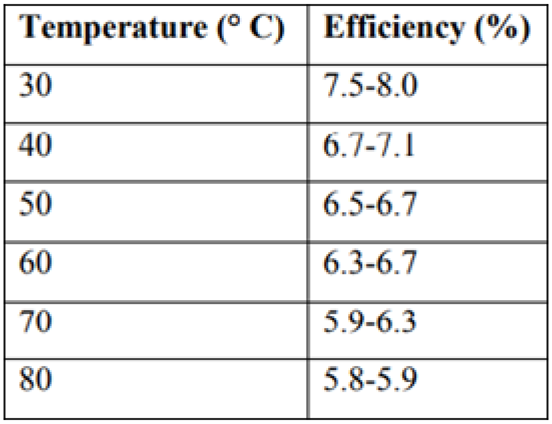
One of the most desirable properties of DSSC is to increase the band gap of the semiconductor material, which highlights the significance of the dye as a critical component of the system. Dye synthesis will meet this need by improving the efficiency of the excitation process and extending the wavelength range of excitation. This aids in the absorption of photons from the sun and the production of electrons and holes. The dye is chemically bound to the semiconductor's porous surface. To be valid for DSSC use, the dye must meet certain requirements, such as having an absorption spectrum that covers the entire visible spectrum, including the near-infrared (NIR) region, having anchoring groups to bind the dye to the semiconductor surface, having a higher level of energy in the excited state than the conduction band in the n-type semiconductor, and having a higher level of energy in the excited state than the conduction band in the n-type semiconductor. The Counter electrode (CE)has a significant impact on the DSSC's efficiency. On the CE side, a thin film of theelectrode content, such as Platinum (Pt),will serve as the catalytic sheet. Although itis a very costly material, Pt is used as the counter electrode in DSSC because of its high electrochemical activity, high conductivity, electrocatalytic aptitude, and long-term stability. Pt thin film is applied to conductive oxide glasses such as fluorine- doped tin oxide (FTO) and indium-doped tin oxide (ITO). Due to its high cost, poor corrosion resistance, and limited availability, alternative materials such ascarbon-based materials and conductingpolymers have been investigated to replace Pt. None, however, had the same conductivity as Pt. Transparency is the property of allowing light to pass through without being obstructed. The transparent solar cell (TSC) is used in a variety ofapplications that involve optically transparent solar cells, such as car windows. The arrangement of atoms and electrons in a substance determines its transparency. When an electron's energy difference is equal to the energy of a photon, it absorbs the photon and travels to a higher energy level; in this case, only a small amount of light passes through the material, making it opaque. Since the electron's energy difference is greater than that of the photons in a transparent substance, the electrons will not be able to use the photon's energy, and light will passthrough, making the material translucent. The solar cell's key feature is its ability to absorb light. As a result, researchers are attempting to increase transparency withoutcompromising the cell's efficiency. In orderto fabricate the layers of the solar cell, a synthesised transparent material is needed. As previously mentioned, the solar cell is made up of several layers that are combined together. Finding a transparent conducting material for the counter electrode is thebiggest challenge. The way to achieve a transparent paste is to keep track of the variables that influence transparency, such as:

1. The Shape of synthesis nanocrystals.
2. The process of producing the paste.
3. Absorbing the NIR and UV light andletting the visible light pass through.
4. The Thickness of the deposited paste.

4.2 Efficiency of DSSC

The efficiency of the DSSC is determined by the dye material's properties, such as high absorption and good photontransformation into the final device. Novelty occurs in DSCC due to photosensitization of nano grained TiO2 coating combined with visible optically active dyes, which increases its efficienciesby more than 10% (Badawy,2015; Dubey etal.,2013). These cells face a number of problems, including DSCC degradation andstability issues (Bagher et al., 2015). In thetable 2 below, the effect of temperature on the efficiency of DSCC solar cells is shown:

Table 2: Effect of increase of temperature on efficiency of Dye sensitized solar cells (DSCC)



Temperature (° C)	Efficiency (%)
30	7.5-8.0
40	6.7-7.1
50	6.5-6.7
60	6.3-6.7
70	5.9-6.3
80	5.8-5.9

(Gong and Sumathy, 2012; Sebastian et al., 2004)

4.3 Organic Photovoltaic - Instead of concentrating on the active layer thickness to achieve a transparent solar cell, Richard Lupnt's research group took a different approach in 2011, modifying the molecules of the dye to absorb ultraviolet and near- infrared (NIR) wavelengths (650–850 nm). A heterojunction organic PV (OPV) transmits more than 65% visible light and absorbs in the near-infrared spectrum with an efficiency of 1.3 ± 0.1%. The OPV comprises of a molecular organic donor, chloroaluminium phthalocyanine (ClAlPc), and a molecular acceptor, C_{60}. The cell's anode is coated with ITO, ClAlPc, C_{60},bathocuproine (BCP), and MoO_3, while the cathode is coated with Ag by thermal evaporation. A distributed Bragg reflector is a transparent NIR mirror that is developed separately on a quartz substrate (DBR). A stop band of approximately 88 nm is created by sputtering TiO_2 and SiO_2 layers to a desired thickness. A broadband antireflection (BBAR) coating is coated onthe other side of the quartz. The main goal of this Transparent Solar Cell model is to allow visible light to pass through while absorbing ultraviolet and near-infrared NIRwavelengths, as shown in the schematicbelow:

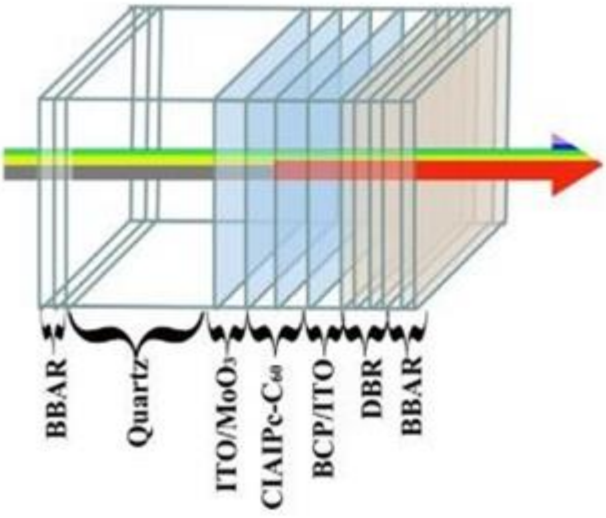


Fig 3.: Transparent OPV

4.4 Quantum Dots PV- Solution- processed nanocrystals, also known as quantum dots (QDs), are used in quantum dot photovoltaics to absorb light. PbS or PbSe QDs have been used as the active layer in the best QD solar cells. The band- gap of colloidal metal chalcogenide nanocrystals can be tuned by changing the size of quantum dots, allowing for the production of multi-junction solar cells andthe effective harvesting of near-infrared photons. The advantages of quantum dot photovoltaics include easy fabrication atroom temperature and air-stable operation.

The excellent optoelectronic properties of QDs have recently attracted interest. The absorption spectrum of QDs changes as they are split into various sizes, making them ideal for solar cell applications. Xiaoliang Zhang (Uppsala University, Sweden) published two TSC models using QD in 2016. The first model employs a PbSQD with a tuneable band gap, which can beused in the infrared range.

PbS QD is therefore an ideal light absorber for solar cell applications. The power conversion efficiency of some heterojunction PbS QD solar cells has been stated to be as high as 9%. In addition, one photon excites more than one hole-electron pair in a PbS QD, breaking the Shockley– Queisser limit for a single-junction solar cell. PbS QD also has a transparent property, making it suitable for semi- transparent heterojunction solar cells. On transparent FTO glass, a semi-transparent solar cell (SCQDSCs) is fabricated using a TiO_2 film as an electron transporting layer (ETL) and a MoO_3 film as a hole transporting layer (HTL). First, a TiO_2 filmis deposited as an electrode; then, using thespin-cast process, a PbS QD thin film is deposited on the TiO_2 film as a light absorber with a band gap energy of 1.3 eV. The bifunctional ligand 3 mercaptopropionic acid (MPA) is handled to increase the charge carrier's mobility within the QD. Finally, a thin layer of 10 nm Au is thermally evaporated on the QD layer; the cell's configuration is shown in the diagram.

Fig 4.: Structure of Quantum Dots Solar Cell

4.5 Efficiency of Quantum dots Solarcells

The PCE varies from 2.04 % to 3.88 %, andthe AVT varies from 32.1 % to 22.7 %, depending on the thickness of the QDs. PbS QDs was used to make a semi-transparent solar cell with 3.88 % PCE and 22 % AVT. The second model had a 5.4 % efficiency and a 24.1 % average visible transmittance. The design and materials used to build this system help to reduce optical loss, resulting in increased performance. This system is ideal for applications requiring low transmittance.

4.6 Perovskites- Perovskite solar cells are a new form of solar cell that have a number of advantages over thin-film solar cells and traditional silicon. Perovskite is a class of compounds described by the formula ABX3, where X denotes a halogen such as I-, Br-, or Cl-, and A and B are different- sized cations. Perovskites are abundant organic materials with excellent electric properties for solar cells, including a high absorption coefficient, high carrier mobility, direct band gap, and high stability. Despite a sharp onset in the absorption spectrum of perovskites,

parasitic absorption in the hole-conducting layer and the back reflector causes significant photocurrent loss. Furthermore, due to a combination of non-uniformity in the absorber (e.g., pinholes) and carrier- selective contacts that contribute to carrier shunting, as well as resistive losses associated with non-ideal carrier-selective contacts, the fill factor in perovskite solar cells is relatively low. High exposure to moisture, cell instability, and the use of toxic lead are all problems.

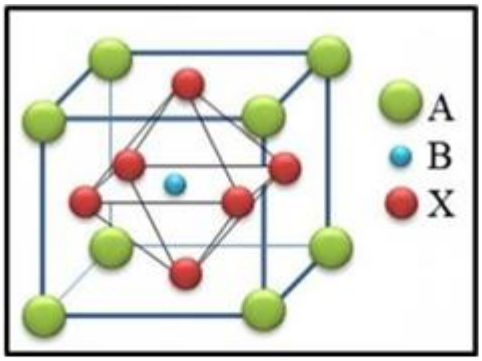


Fig 5: Crystal structure of organometal perovskite

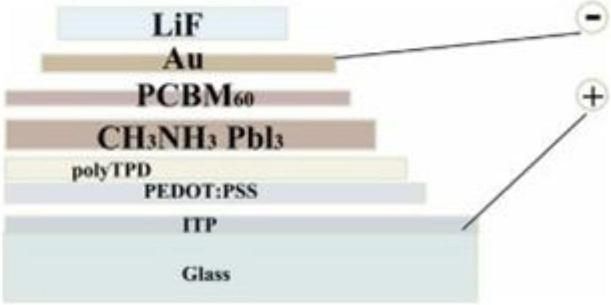


Fig 6: Perovskite solar cell layers

4.7 Efficiency of Perovskites

Park (2015) was the first to record stable perovskite solar cells with conversion efficiencies as high as 9.7%. When the temperature rises from -80°C to 80°C, Jacobsson et al. (2016) found that output drops by up to 25%. (Shi, 2015) These solarcells have a 31 % yield. Certain problems with perovskite solar cells include stabilityand longevity. The efficiency of this cell isreduced as the material used in it degrades.

5. Conclusion

The deep analysis of different varieties of Solar cells was done and their efficiencies were also noted. Solar power generation hasemerged as one of the most challenging renewable energy sources to develop. It has a myriad of advantages overother energy sources such as fossil fuels and petroleum resources. It is a promising and dependable alternative for meeting the growing energy requirements. Though the methods for harnessing solar energy arestraightforward, they do necessitate the useof a solar material that is both efficient andlong-lasting. Solar cells based on nano- crystal QD of semiconductors technology have the potential to convert more than 60%of the solar spectrum into electricity. Solar cells with a polymer base are also a potential choice. Their deterioration over time, however, is a severe worry. Cutting production costs, improving public awareness, and providing the best infrastructure are just a few of the challenges this industry faces. Solar energy is becoming highly significant, and solar cell research has a promising future worldwide.

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