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Design and Analysis of Various Solar Cell Technologies for Improvements in Efficiencies

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Solar cells have undergone massive evolution since the development of first commercial solar cell by Bell laboratories in 1954. Its chronological journey includes crystalline silicon solar cells of first generation followed by thin film solar cells of second generation to perovskite solar cells of latest third generation technology. Among these, Silicon based solar cells of first generation have been highly commercialized due to its durability and cost effectiveness. However, their efficiencies are major concern which have been constrained to 27% till date since their origin. On the contrary, perovskite solar cells of third generation have undergone outstanding transformation in just 12 years with rapid increases in certified efficiency, from 3.8% in 2009 to 25.6% till date. However, stability is major problem with these cells, which makes these cells poor contender for commercialization. Nevertheless, researchers are optimistic to enhance performance and prolonged stability of these cells in forthcoming years as perovskite layers are quite easy to develop in laboratory by mixing various salt solutions together to form a thin film. Currently, photovoltaics is widely used in space, telecommunications, remote power, cathodic protection and other day to day usage. The current maximum global capacity of solar energy is 592 GW, contributing nearly 2.5% to global electricity generation. Objective of this paper is to review development of solar cells since its origin, with comprehensive description of manufacturing processes, costs, implementations and power conversion efficiencies of solar cells of various generations including their future trends and aspects.

Keywords: CIGS, Current photovoltaic technologies, Efficiency, Perovskites, Thin film, Wafer silicon based solar cells

1 Introduction

Photovoltaic has been proved as an intensive technological approach to transform sunlight into electrical energy. Electricity, being the direct current, may be used as alternating current by converting it and can be stored for further exploitation. Hypothetically, a photovoltaic cell is a device that only ingests sunlight and yields electricity. Absence of moving parts, at least not in the atomic way, makes its operation appropriate for the environment. Photovoltaic devices, being eco-friendly and non-toxic, have been proved beneficial and suitable for inhabitants of earth. Photovoltaic systems being flexible in design, their power output have been utilized for almost every application *i.e.* from low powered consumer uses *e.g.* wrist-watches, toys, calculators and battery chargers to high power consumer uses *e.g.* solar arrays of space satellites[1].

The vital parameters required to examine the capability of a solar cell are short-circuit current density (J_{SC}), fill factor (FF), open-circuit voltage (V_{OC}) & power conversion efficiency (PCE). J_{SC}-V aspects of a solar cell in dark and illuminated environment has been illustrated by Fig. 1. Short-circuit current density (J_{SC}) has been elaborated as the current generated by a solar cell under illuminated environment in the absence of any external load. Open circuit voltage (V_{OC}) has been stated as the difference in potential across two terminals of a solar cell under illuminated condition while no current passes across the terminals[2]. Fill Factor (FF) has been elaborated as the ratio of maximum power (P_{max}) generated to the product of short-circuit current density (J_{SC}) and open-circuit voltage (V_{OC}) *i.e.*[2]

$$FF = P_{Max} / \{(J_{SC})\times(V_{OC})\} \qquad \ldots(1)$$

Power conversion efficiency of a PV (Photovoltaic) cell has been described as ratio of the maximum power generated by the solar cell and the incident radiant energy.

2 Materials and Methods

2.1 Technologies implemented in solar cells

It has been experienced that present day solar cells have some disadvantages but these would be possibly astounded with the advancement of new technologies.

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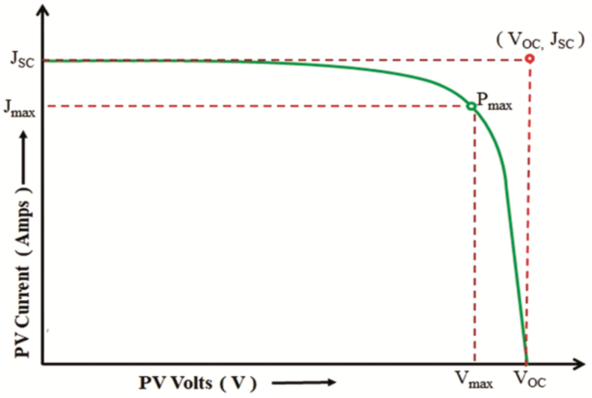

Fig. 1 — Voltage / Current characteristics.

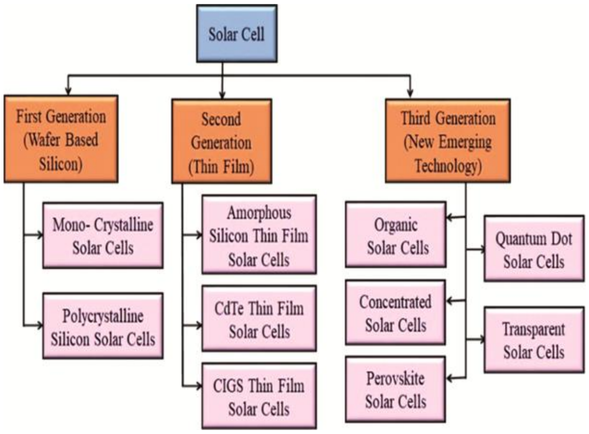

Fig. 2 — Various solar cell technologies, and trending developments.

Subsequently, the cost of solar cells along with installation will decrease so that these cells will be within the reach of common man. Presently, search for new materials with properties like low specific gravity, malleable, inexpensive and non-toxic is in progress to manufacture cost effective and reliable solar cells with higher efficiencies.

The journey of manufacturing processes *w.r.t* solar cells has seen numerous transformations starting from wafer silicon based to new emerging technology of third generation which has been illustrated through Fig. 2[3]. Developments of next generation solar cells have boosted the efficiencies of these cells[3]. Solar cells have been differentiated into a number of classes as per materials utilized which are elaborated in the succeeding sections.

2.1.1 First Generation Solar Cells (Wafer Silicon Based)

These cells have been recognized as conventional solar cells which are fabricated on thin silicon layers called wafers. These cells are the most geriatric and have involved eminent technology due to its high energy conversion rates. These cells have been further classified into Mono-crystalline/Single crystalline silicon solar cell and Polycrystalline/Multi-crystalline silicon solar cell.

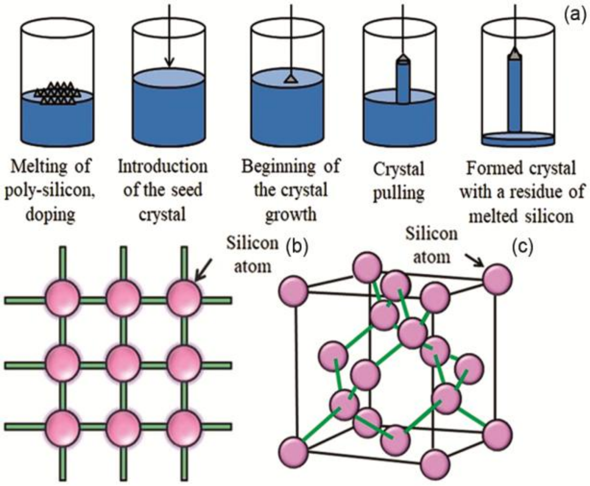

Fig. 3 — (a) Czochralski process, (b) Crystal structure of Si in 2-D, and (c) Crystal structure of Si in 3-D.

As mentioned by its nomenclature, the entire volume of single crystalline silicon solar cell is a single crystal of silicon. The manufacturing of these crystals was initially done using Czochralski process which is depicted in Fig. 3(a)[4,5]. Following steps were involved in these processes *i.e.*melting of highly pure polysilicon, dipping of minute crystals deposited over a rod into the molten silicon, simultaneously pulling and rotation of the rod upwards, removal of a single, large crystalline ingot (It involves adjustment in temperature, crystal pulling rate and rpm).

Post formation of silicon ingots, thin wafers of about 0.2-0.8mm thick were cut from these ingots which further got polished to a very high flat surface. The whole process required a precise processing. Further, thin wafers were recrystallized with fusible metal tin (Sn) by the process of recrystallization. Although, mono-crystalline silicon solar cells were costly as their fabrication involves multiple processes yet these were chemically stable with negligible defects. The power conversion rates of these cells were initially found to be 17% - 18%[3] which has been now enhanced to 27.6%[6]. Crystal structure of silicon in 2D and 3D is illustrated in Fig. 3(b & c) respectively[7].

Major drawback of these cells was that these cells did not operate efficiently whenever the ambient temperature rises above 25°C. Therefore, an effective air circulation system surrounding the panel are used for exchanging heat to avoid unnecessary heating and to increase the efficiency of these cells[8].

Poly/ Multi-crystalline silicon solar cell was initially manufactured by heating trichlorosilane sedimentation over the silicon rods to a specific temperature. Distinct crystalline configurations were moulded post solidification of molten silicon[5,9]. Polycrystalline silicon solar cells were comparatively inexpensive to fabricate in comparison of mono-crystalline silicon solar panels because of low processing cost, however the former was comparatively lesser efficient *viz* 23.2%[6]. Almost half of the total solar cells manufactured worldwide in 2008 were limited to these cells only. Even today, these cells are high in demand among various nations. Ribbon Silicon is very good example of these cells.

2.1.2 Second Generation Solar Cells (Thin Film based)

Initially, thin film solar cell was synthesised by stacking up of very thin layers of the order of 1 µm (1 micro meter) of light absorbing materials on a substrates of plastic, glass or metals. Whereas the thickness of silicon wafers was taken 300 µm (micro meter). Hence, it was appreciated as thickness of these cells had been nearly 300 times thinner than the silicon wafers[3]. In addition to lesser thickness, these cells were comparatively flexible and attained lower weight than the conventional first generation cell. For synthesis of thin film solar cell, copper based ternary chalcogenides (here chalcogens refer to elements of group16 in the periodic table) with general formula Cu_aBX_b {where B is Tin (Sn), Antimony (Sb), Bismuth (Bi) and X is Selenium (Se), Tellurium (Te), Sulphur (S)} have been intensely used as *p*-type materials. As copper antimony sulphide ($CuSbS_2$) is abundantly available on earth, its cost has been very low. Also, $CuSbS_2$ was preferred to $CuInS_2$ as the former occupied direct band gap of 1.5eV while the latter sustained 1.02eV. Further, for nearly equal ionic radii, Antimony was economical to Indium. Presently, hot injection method is in demand for manufacturing nano-plates and nano-particles of copper antimony sulphide ($CuSbS_2$) with commensurate optical and structural properties. Subsequently, this method resulted in maintaining shape and size uniformity. Thin film group of solar cells can be listed as Amorphous silicon cell (a-Si), Cadmium Telluride cell (CdTe), Copper Indium Gallium Selenium cell (CIGS)[10].

Amorphous Silicon *i.e.* a-Si (a non-crystalline structure) solar cells were fabricated by cladding the doped silicon over a flexible or a glass substrate. This was done by highly sophisticated Plasma Enhanced Chemical Vapour Deposition (PECVD)[7]. It was observed that the visible light had incidented on the uppermost layer of a-Si and a part of incidented light was landed on the bottom of cell while rest of the light was reflected back. Amorphous Silicon constituted a band gap of 1.7eV which was greater than that of c-Si. Schematic representation of chemical bonding in a-Si and a-Si: Hydrogen is illustrated in Fig. 4(a) and Fig. 4(b) respectively[7]. Schematic stacking of different layers in a typical a-Si cell is illustrated through Fig. 4(c)[7]. Main demerit of a-Si cells was that their conversion efficiencies were almost unstable fluctuating from 4% to 8%. However, these cells could be performed satisfactorily at higher temperatures. Presently, these cells are adapted to variable weather conditions where intensity of sunlight is not optimum. The efficiency improvement of a-Si has taken a leap from 2.4% to 14 % between 1976 and 2020 which is depicted through Table 1[11-14,6].

Though cadmium (Cd) is a highly toxic element and tellurium is available in scarcity yet Cadmium Telluride (CdTe) was considered better selection for fabricating low cost photovoltaic device. Its manufacturing technology was inexpensive, in addition it possessed the optimum band gap of approx. 1.45eV which permitted the absorption of light easily, resulting in increased efficiency of solar cell. Since cadmium and tellurium belong to group 12

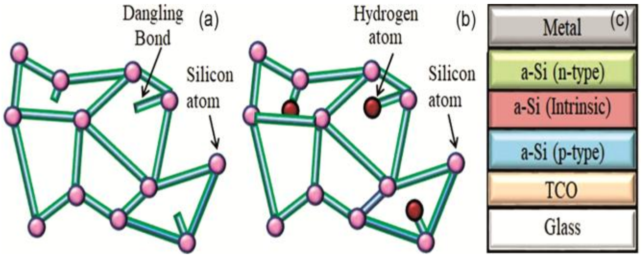

Fig. 4 — Schematic representation of chemical bonding in (a) a-Si (b) a-Si:H, and (c) Schematic arrangement of various films in typical amorphous Si solar cell.

Table1 — Development of a-Si solar cells & their conversion efficiencies between 1976-2020

Sr. No.	Efficiency η (%)	Year	Ref. No.
1	2.4	1976	11
2	9.3	1986	12
3	11.8	1996	13
4	13.6	2015	14
5	14	2020	6

and group 16 of the periodic table respectively, these elements possessed high optical absorption and chemical stability. Subsequently, these elements have become the most appropriate contender for processing thin film solar cell[15]. Crystal structure (zinc blend cubic) of CdTe solar cell is illustrated in Fig. 5(a)[7]. Schematic diagram of CdTe solar cell with requisite layers of materials is illustrated in Fig. 5 (b)[7]. The efficiency improvement of CdTe cell has seen a rise from 6% to 22.1% between 1972[16] and 2020[6].

Copper (Cu), Indium (In), Gallium (Ga) and Selenium (Se) are the main building blocks of CIGS cells which represents the group 11, group 13, group 13 and group 16 respectively of the periodic table. CIGS has general molecular formula of [$CuIn_xGa_{1-x}Se_2$]. Copper Indium di Selenide *i.e.* x=1 was initially developed which had favourable optical and electrical properties with band gap 1.04eV. On further investigation, it was found that its energy level could further be increased to 1.68eV by replacing indium with gallium[7]. However, only a partial replacement of indium with gallium was done to keep the resistivity of material at optimum level. Therefore, by changing the ratio of quantity of indium to gallium one could tune the forbidden gap between 1.04eV-1.68eV as per requirement. Further, CIGS materials had an optical absorption coefficient of 10^{15} per cm for 1.5eV. Crystal structure of CIGS is illustrated through Fig. 6(a)[7]. CIGS structure and various layers of described cell is illustrated in Fig. 6(b)[8] & Fig. 6(c)[7] respectively. The efficiency improvement of CIGS cell has jumped from 4.5% to 23.3% between 1976[17] and 2020[6].

2.1.3 New Emerging Technologies (Third Generation Solar Cells): Besides First and Second generation solar cells, new emerging technologies also known as Third Generation or multi-junction solar cells have also evolved which exhibit improved electrical conductivity while retaining very low manufacturing costs. Recent researches are aiming the efficiencies of 30% to 60% with low-priced materials and manufacturing techniques. Types of various third generation cells are Organic solar cells (OSC), Quantum dots (QD) solarcells, Concentrated solar cells (CPV), Transparent solar cells (TSC), Perovskite solar cells (PSC).

Organic solar cells comprise of carbon & hydrogen compounds along with halogens, chalcogens and pnictogens. These cells were initially manufactured using organic polymers. Organic polymers behave like conductors by displacing π electrons and adding of sulphur as doping agent *e.g.* P3HT {poly(3-hexylthiophene-2,5-diyl)} and PCBM {[6,6]-Phenyl-C61-butyric acid methyl ester} behave as donor and acceptor respectively[18].

A single layer OSC consists of a single film of photo sensitive material. This cell's configuration has failed to touch the standard energy efficiencies due to limitations of organic constituents and demand of energy for splitting of excitons which was quite high as depicted in Fig. 7(a) and Fig. 7(b)[19].

Later in mid-eighties, materials with lower Ionization Potential/Lowest Unoccupied Molecular Orbit

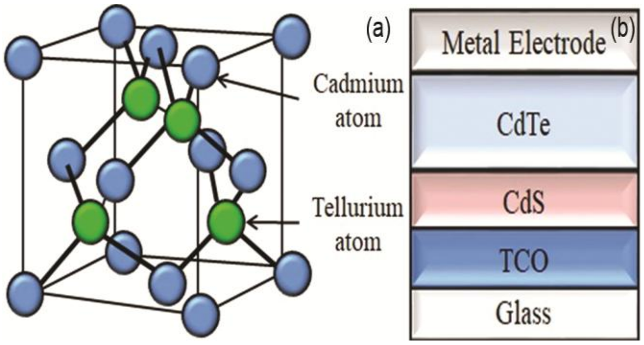

Fig. 5 — (a) Crystal structure (zinc blend cubic) of CdTe[7], and (b) Standard Structure of CdTe/CdS Solar Cell[7].

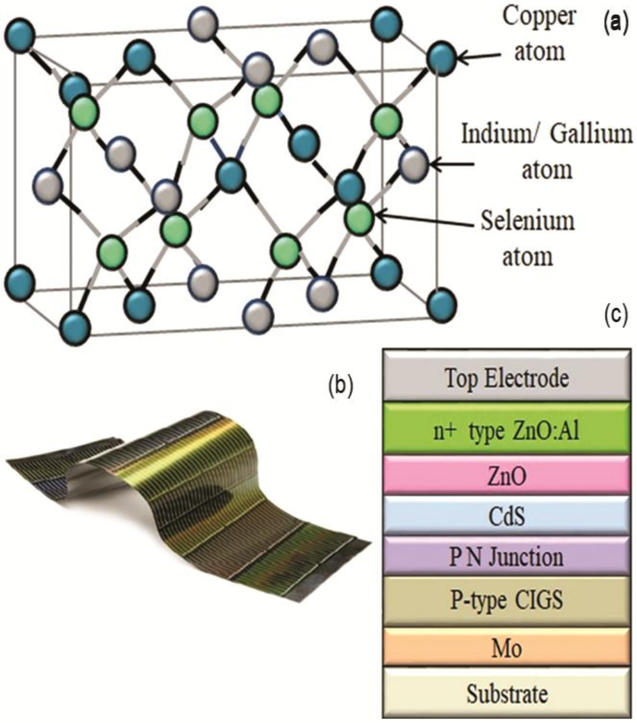

Fig. 6 — (a) Crystal structure of CIGS chalcopyrite, (b) CIGS Solar Cell[8], and (c) Layers in CIGS Solar Cell[7].

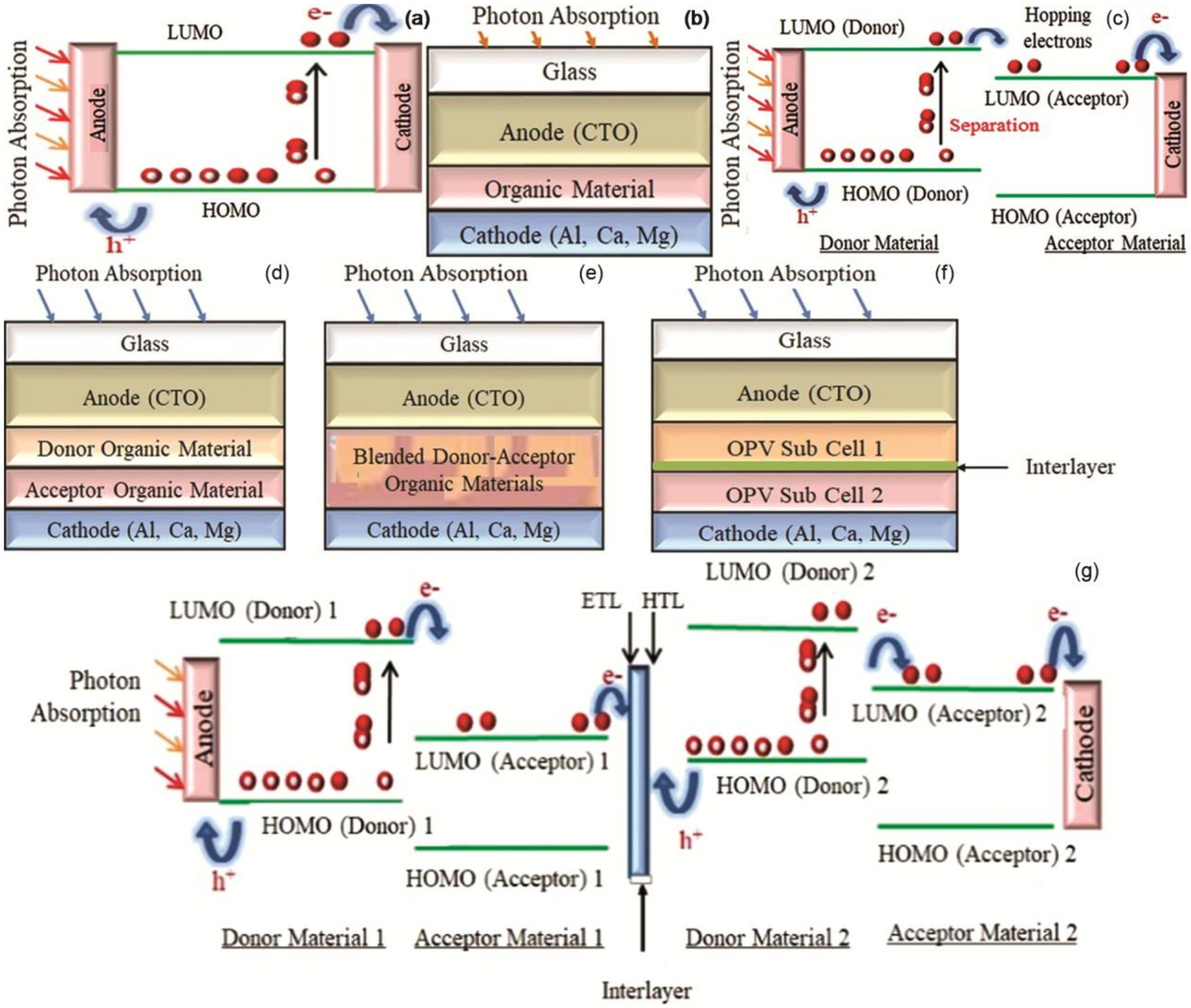

Fig. 7 — (a) Simplified Energy Diagram of a single Layer OSC, and (b) Single layer OSC, (c) Simplified Energy Diagram of a Bi-layer Hetero junction Solar Cell, and (d) Bi-layer Hetero junction Solar Cell, (e) Bulk Hetero junction, and (f) Tandem Hetero junction Solar Cell, (g) Simplified Energy Diagram of a Tandem OSC.

(IP/LUMO) were discovered that could effortlessly provide electrons. In addition, materials with higher Electron Affinity/ Highest Occupied Molecular Orbit (EA/HOMO) were also observed that could receive electrons without any difficulty. Subsequently, a dramatic increase in efficiency were observedby introducing a donor and an acceptor simultaneously in one cell which paved the way for the birth of first heterojunction photovoltaic cell[19]. In these devices, photocurrent generation process included formation of excitons (electron-hole pair) followed by absorption of light packets, diffusion of excitons towards the junction, the splitting of excitons into separate holes and electrons, transportation and accumulation of holes and electrons at respective electrodes.

The heterojunction cells were further classified into Bi-layer heterojunction, Bulk Heterojunction (BHJ), Tandem Heterojunction structures. A bilayer heterojunction solar cell also named as planar OSC consisted of two closely connected thin films of donor and acceptor material packed between two electrodes as depicted in Fig. 7(c)[19]. The main drawback of planar OSC was that excitons formed near the junction (<~20nm) dissociated only, at larger distances (>~20nm) *w.r.t* junction. The electrons and holes thus produced were recombined prior reaching donor-acceptor junction because of low mobility and short diffusion length. Consequently, the planar heterojunction failed to achieve higher efficiency. To ameliorate the proficiency of bilayer organic heterojunction, efforts were made to reduce the film thickness of photosensitive layer to the order of diffusion length of excitons. However, the same were resulted in the formation of ultra-thin film with lower light absorption, subsequently; lesser number of excitons were produced. A typical bilayer heterojunction is depicted in Fig. 7(d)[19].

A Bulk Heterojunction (BHJ) solar cell also defined as Dispersed Heterojunction consisted of blended donor-acceptor semiconductor materials as shown in Fig. 7(e)[19]. Consequent to this arrangement, the excitons could easily be dissociated into separate electrons & holes and could be simply diffused to adjoining interface. This configuration had shown much higher PCEs than the Bilayer/Planar Heterojunctions. Normally, both configurations *viz* small-molecule based bulk Heterojunction & polymer based bulk Heterojunction exhibited highest PCEs. In recent time, researchers are more enthusiastic in P3HT:PCBM based BHJ OSC[19].

As light absorption in single layer, planar heterojunction and BHJ OSCs were found restricted, Tandem Heterojunction cells came into light which could absorb energy packets from the short wavelength zone as well as from the long wavelength zone. Tandem OSCs had become famous for its unique feature of maximizing the solar spectrum absorption. As depicted in Fig. 7(f) and Fig. 7(g), tandem configuration was comprised of two BHJ cells with corresponding photo absorption spectrum, parted by an interconnecting layer designed to gather charged particles created within the cells. This interconnecting layer resulted in the adjustment of the quasi-Fermi levels of the bottom and the top cell[19].Van der Waal bonding within an organic tandem solar cell eradicated the problem of photo-voltage loss to large extent which had occurred because of thermalization of hot charge carriers, produced when photons possessing energy higher than that of band gap were consumed. Consequently, these cells were inexpensive and possessed higher efficiency.

Power conversion rate of organic solar cells has been shooted drastically during recent years. Since the materials used in these cells are degradable, these cells suffer smaller life. Consequently, introduction of these cells in market has become a cumbersome job. The maximum energy conversion rate of organic solar cell has been recorded 18.22% till 2020[20].

Burnham and Duggan[21] (1990) used Quantum dots (QDs) for the first time in solar cells for ebbing undesirable energy losses with involvement of semiconductors of varying energy levels[21]. QDs were the semiconductor nano-particles, usually derived from transition metals of the size of few nanometers equivalent to exciton Bohr radius. Energy levels of QDs could be regulated by altering the dimensions of particles which were not feasible with energy level of same semiconductor of larger size. Hence, QDs had undoubtly become the favourable candidate for multi-junction solar cells because of its flexibility in tuning of band gaps. Formerly, QDs were manufactured using MCVD (Modified Chemical Vapour Deposition) technique[21]. Later on, these were prepared by wet chemical processing which was an inexpensive and simpler process. Working procedure of a quantum dot solar cell is described through Fig. 8(a)[22]. Chuang *et al.*[23] manufactured single-junction PbS (Lead Sulphide) Quantum Dot solar cells. Initially, a glass substrate was layered with ITO (Indium Tin Oxide). Further, a very thin coating of ZnO (Zinc Oxide) was coated over ITO coated glass substrate using spin coating technique followed by deposition of PbS Quantum dots coated with oalic acid using solution processing with tetrabutyl-ammonium iodide (TBAI) and 1,2-ethanedithiol (EDT). At last, gold was deposited to the resultant stack as an anode using thermal evaporation technique in vacuum Photon absorption by quantum dots resulted in production of free charged particles which got collected at respective electrodes because of internal electric field generated due to Fermi level orientation of two electrodes. The cell with twelve layers of TBAI processed QDs displayed 6% energy efficiency. However, substituting the upper two layers of PbS-TBAI with PbS-EDT layers enhanced the energy efficiency to 9% because these PbS-EDT layers operated as hole transport and e^- blocking layer. Interestingly, QDSCs ejected more electrons compared to first generation cells at the cost of each photon. Production of these cells were found cheaper as compared to other photovoltaics because these were processed from solution. The practical energy efficiency of these cells was observed approximately 2.5% against hypothetical energy efficiency which was observed to be 45%[7]. Schematic diagram of QDs solar cell is depicted vide Fig. 8(b)[22]. The efficiency of QD has been upgraded from 1.46% to 16.6% during the period 2009[24]- 2020[6].

Concentrator PV cell is a cell which is illumined by sunlight that usually converged by employing convex lens or concave mirror. The concentration of sunbeam is vital for actualizing solar cells, exhibiting energy

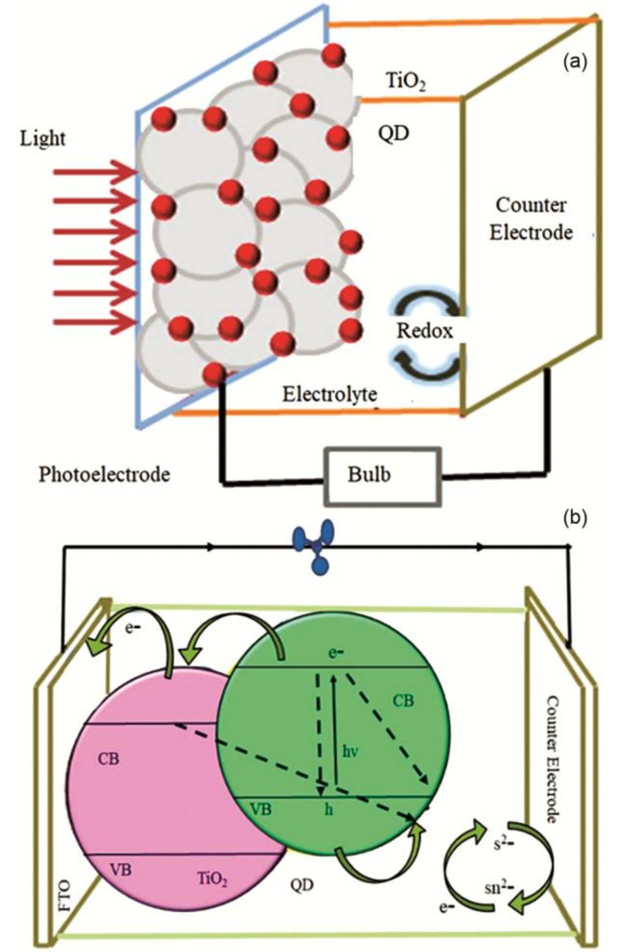

Fig. 8 — (a) Basic structure of a QDSC, and (b) Structure of photo induced charge transfer process.

conversion efficiencies above 45%, aiming at 50%. Fig. 9 depicts the simple arrangement of a concentrator PV cell[25]. Concentrator solar cell was first come into light in 70s. These cells functioned on the fundamentals of ray optics[25]. They consisted of assembly of big converging mirrors and lenses that intended a surge in the power conversion efficiency by converging sunlight that usually failed to fall on the cell surface. Subsequently, a significant amount of thermal energy was generated. In the domain of solar cells, the concentrated solar cell technology has revealed its boosting persona. Based on the arrangement of lenses and mirrors, these cells have been categorized into low, medium & high concentrated PV cells. These cells have exhibited maximum PCE of 38.9%[3]. Devoid of moving accessories, swift riposte, low operating charge and performance at atmospheric temperature are some of the significant features of these cells.

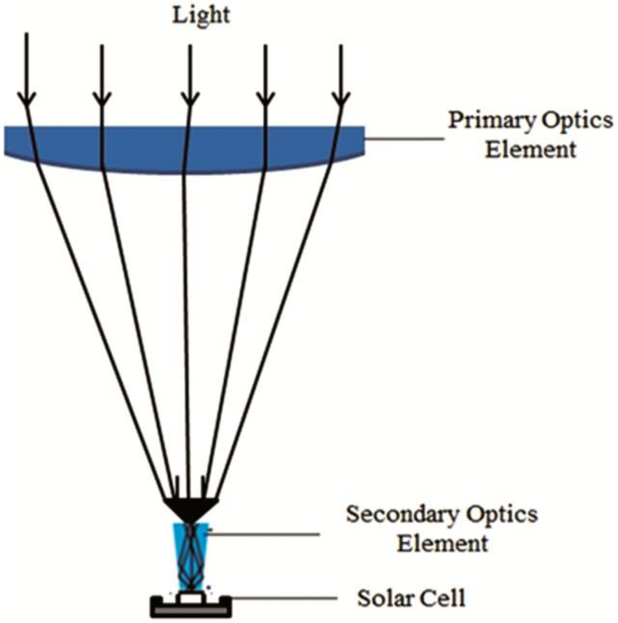

Fig. 9 — Structure of concentrating photovoltaic cell.

Earth receives plenty of sunrays but a large portion of it goes vain and the balance energy is limited to solar farms and panels of rooftops. Currently, TSCs have attracted the consideration of scientists due to their increased utilization in society. These cells have been commercialized in many countries while some nations are considering for its utilization in forthcoming years post significant enhancement of their efficiency. TSCs exhibited the capability to yield the energy equal to 40% of energy exploitation of buildings provided the availability of TSCs possessing 90% of glass over exterior of each structures/buildings. Not with standing, many developed and developing countries including India have been utilizing transparent solar cell technology in automobiles and electronic gadgets. Initial Transparent solar cell consisted of an ITO or FTO film coated on a glass substrate, having 10Ω per square resistance along with a layer thickness of approximately 20nm. In addition to intrinsic optical reductions of glass itself, these films decreased the transparency of cell by 15% -20% prior another layer was piled. Till date nearly 80% of transparency is attained[26]. Figure 10 illustrate the compositions of the early TSC[26,27]. An ultra-sensitive layer against UV (Ultravoilet) and NIR (Near Infra-Red) radiations was sandwiched between both electrodes which was transparent. The cell had PBDTT-DPP and PCBM as e- donor and e-acceptor respectively, and both were combined to form a proactive PBDTT-DPP: PCBM

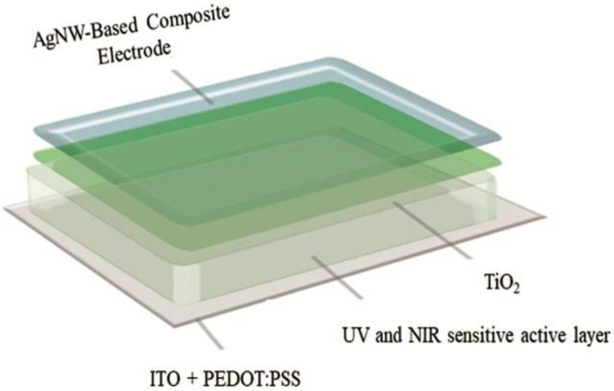

Fig. 10 — Schematic architecture of a transparent solar cell[26].

layer. 73% and 68% were the maximum and average transmission respectively for the photoactive material *w.r.t* visible region (400nm to 650nm). Nonetheless, a UV along with NIR region sturdily engrossed light. To modify the cell, the anode substrate, ITO; coated with PEDOT: PSS(Poly(3,4-ethylenedioxythiophene) polystyrene Sulfonate) was positioned as the bottommost layer. Since the organic materials was quite sensitive, the electrode needed to be positioned at the topmost though this might not sustain the film sedimentation procedure. To prevail over the scenario, a thin coat of AgNW (Silver Nanowire) was layered by spraying technique over the resultant stack. AgNW was stuck to the photosensitive film in presence of TiO_2 sol-gel solution. It needed minute processing[27]. The efficiency of TSC cells has been increased from 4% to 8.02% within the period from 2012[27]- 2014[28]. Scientists are now working towards the boosting of the efficiency of TSC without compromising its transparency; the same will be probably achieved in the forthcoming years.

LA Perovski, a Russian scientist, discovered Calcium Titanate, $CaTiO_3$, in 1839, possessing an orthorhombic crystal symmetry in which larger Ca^{2+}ions were positioned at the corners while smaller sized Ti^{4+} were positioned at the body cubic centre and O^{2-} were situated at face centre in the structure hence was named perovskite in honour of the Russian scientist. Post this discovery, materials with chemical composition CDX_3 & crystal structure identical to $CaTiO_3$ were identified as perovskites where C, D and X were analogous to Ca^{2+}, Ti^{4+} and O^{2-}. The perovskites exhibited a highly stable three dimensional network structure. Some common perovskites are $CsSnI_3$ (Cesium Tin Iodide), $FAPbI_3$ (Formamidinium Lead Iodide), $CaTiO_3$, $MAPbI_3$ (Methyl Ammonium Lead Iodide), $MAPbBr_3$ (Methyl Ammonium Lead Bromide) and $MASnI_3$ (Methyl Ammonium Tin Iodide). The perovskites possess many magnificent properties *viz* superconductivity, spintronics & magnetoresistance. Kojima*et al.*[29]were the first to use perovskites as a photoactive material in a DSSC (Dye Sensitized Solar Cells). In 2009, they utilized $MAPbI_3$ & $MAPbBr_3$ as photoactive materials, mesoporous TiO_2 (m-TiO_2) as ETM. LiI/I_2 in CH_3OCH_2CN(Methoxyacetonitrile) and $LiBr/Br_2$ in CH_3CN (Acetonitrile) had been taken as electrolytes *i.r.o* MAPbI and MAPbBr respectively for two separate DSSCs. However, they exhibited lower efficiencies 3.81% and 3.13% respectively. In addition, these cells were unstable. In 2012, Kim *et al.*[30] were the first to synthesize $MAPbI_3$ sensitized solar cells using spiro-OMeTAD(2,2',7,7'-Tetrakis [N,N-di(4-methoxyphenyl)amino]-9,9' spirobifluorene) as HTM (Hole Transport Material) in solid form. Surprisingly, this cell exhibited the energy efficiency of 9.7% which provoked the scientists for perovskite materials that led to the rise to unique type of solar cells termed as perovskite solar cells.

The initial perovskite solar cell used FTO shielded with glass substrates. Further, the substrate was deposited with thin film TiO_2 using spin coating method followed by annealing at nearly 500^oC for the duration of 20 minutes. The compact layer developed, acted like ETM (Electron Transport Material) and constrained the hole activity. Additionally, it behaved like a barrier between FTO and perovskite layer. Thereafter, a layer of m-TiO_2 was encrusted upon compact deposition of TiO_2 through the process of doctor blading, followed by sintering carried out for the duration 45 minutes at 550^oC. After that, the resultant compound was layered by employing $MAPbI_3$, accompanied by heat treatment at 100°C for the duration of 10 minutes. Subsequently nanocrystal $MAPbI_3$ developed over m-TiO_2 coating. Further, a film of spiro-OMeTAD was coated onto $MAPbI_3$ using spin coating technique[31]. This film acted as HTL. At last, the cell was accomplished with final sedimentation of thin layer of gold (Au) by employing thermal evaporation process. Crystal and Schematic view of Perovskite cell is depicted in Fig. 11(a) and Fig. 11(b) respectively[7].

Burschka*et al.*[32] in 2013, elaborated an advance procedure for built-up of perovskite film onto m-TiO_2 layer that gave rise to controlled configuration of perovskite film. Moreover, this resultant perovskite film had the ability to be adsorbed deeply in m-TiO_2

film which previously was not feasible. As a result, PCE of the cell touched the limit of 15%. Over the past few years, Zhou*et al.*[33] exalted the efficacy of ETL by addition of yttrium (Y) in the compact TiO_2 layer that led to increase in cell efficiency upto 19.3%. Ultimately, the energy efficiency rate of perovskite cells shoot up to 25.6% from 3.8% till 2021 as shown in Table 2[29,30,34-36].

Perovskite layers were manufactured using solution based process and vapour deposition process[37-40]. These processes had been further divided into sub processes as illustrated in Fig. 12 and are elaborated in succeeding paragraphs[40].

Solution based process employed an easier and cost effective method for coating perovskite layer on the substrate. This coating was further prepared by two techniques, *i.e.* one-step spin coating process and two-step spin sequential deposition process[31].

In one-step spin coating process, a solution of methylammonium halide (MAX) powder and lead halide (PbX_2) in 1:1 ratio or a solution of methylammonium halide (MAX) powder and polar solvents like gamma-Butyrolactone (GBL), N,N dimethylformamide (DMF) and dimethyl sulfoxide (DMSO) in 3:1 ratio was spin coated onto the previous substrate. The substrate formed was further annealed at specific temperature as per the solvent utilized. The film acquired using this process exhibited amorphous configuration[31,39].

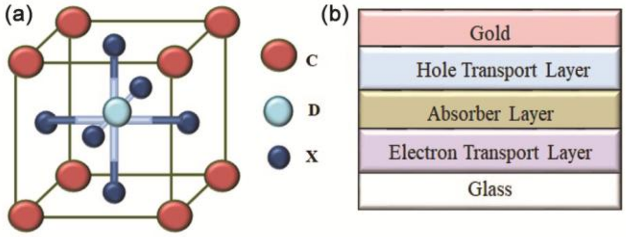

Fig. 11 — (a) Perovskite Crystal, and (b) Schematic presentation of Perovskite solar cell.

In two-step spin sequential deposition process, a film of PbI_3 was spin coated onto m-TiO_2 (mesoporous Titanium Oxide) layer. The substrate formed was further exposed to 2-propanol (IPA) solution containing adequate methylammonium iodide. With this technique, efficiency of perovskite solar cells extended to 15%. The film formed using this technique exhibited cubic crystal structure[31,39].

Vapour deposition method was introduced by Liu *et al.*[40] to develop perovskite film. In this technique, MAI and $PbCl_2$ were simultaneously deposited on fluorine-doped Tin oxide (FTO) substrate using evaporation method from two separate containers placed at 120°C and 350°C, respectively, in a nitrogen-filled glove box in vacuum. Thus, a coating of $MAPbI_{3-X}Cl_X$ was developed post annealing at a particular temperature. This was an expensive process. This method was further being classified into chemical vapour deposition and physical vapour deposition[40].

Vapour assisted solution processing technique is a low-temperature film forming technique. The layer of perovskites formed using this process exhibited full

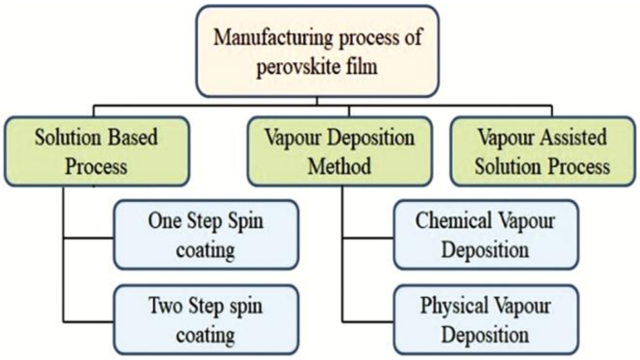

Fig. 12 — Fabrication techniques of Perovskite Solar Cell.

Table 2 — Progress in perovskite cells *w.r.t.* efficiencies during 2001-2020

Sr. No.	Structure	Voc (V)	Jsc (mA per cm^2)	FF (%)	Efficiency η (%)	Year	Ref. No.
1	Glass/FTO/bl-TiO_2/mp-TiO_2/ $MAPbI_3$/Redox Liquid electrolyte/Pt	0.61	11	57	3.81	2009	29
2	Glass/FTO/bl-TiO_2/mp-TiO_2/ $MAPbI_3$/Spiro-MeTAD/Au	0.888	17	62	9.7	2012	30
3	Glass/ITO/np-ZnO/ $MAPbI_3$/Spiro-MeTAD/Ag	1.03	20.4	74.9	15.7	2013	34
4	Glass/FTO/bl-TiO_2/mp-TiO_2/$Cs_x(MA_{0.17}FA_{0.83})_{(1-x)}Pb(I_{0.83}Br_{0.17})_3$/Spiro-OMeTAD/Au	1.157	22.55	76.6	21.1	2016	35
5	Glass/FTO/c-TiO_2/ m-TiO_2/α-$FAPbI_3$/ OAI/Spiro-OMeTAD/Au	1.189	26.35	81.7	25.6	2021	36

Table 3 — Comparison w.r.t fabrication cost of various solar cells

Generation of Solar Cell	Name of Solar Cell	For Efficiency (%)	Cost [in Rupees per watt at peak performance (W_P)]
First Generation	Mono crystalline silicon solar cell	19	42
	Poly crystalline silicon solar cell	17	36
Second Generation	Amorphous silicon solar cell	7	49
	CdTe solar cells	16	33
	CIGS solar cells	14	24
Third Generation	Organic solar cells	5	70
	Quantum dots solar cells	20	60
	Concentrator photovoltaic cell	35	70
	Transparent solar cell	17	45
	Perovskite solar cell	19	28

surface coverage and evenly formed micro-sized crystal grains. This process was cheaper compared to vapour deposition methods[31,39].

Comparison *w.r.t* fabrication of various solar cells is tabulated in Table 3[41-43]. Further, durability and stability of perovskite cells need notable improvement[44-46]. Nonetheless, scientists are highly optimistic to fabricate the perovskite cells of higher power efficiencies with very low cost and higher durability.

3 Results and Discussions

The commerciality of a solar cell relies upon availability, cost and its efficiency. The cost is measured in Rupees per Watt at peak performance (W_p). Solar cells of various generations have been briefly discussed in previous sections. First generation solar cells are widely used in almost every sector because of availability of raw materials and its commercialization owing to its adequate efficiency at manageable cost per Watt at peak performance *viz* Monocrystalline solar cells cost around Rs 42 per Watt peak performance for exhibiting 19% efficiency on the other hand, second generation solar cells are relatively cheaper compared to first generation however, the second generation solar cells exhibit lower efficiency than first generation solar cell. Among the second generation solar cells, CdTe cells cost around Rs 33 per Watt at peak performance against 16% efficiency. Third generation solar cells are newest & promising photovoltaic cells. Though the efficiency of these solar cells are relatively higher than the first & second generation solar cells; yet their cost per Watt at peak performance for producing same efficiency is very high compared to first & second generation cells. Among third generation solar cells, concentrated photovoltaic cells cost around Rs 70 per Watt at peak performance for producing 35% efficiency. Besides high cost, concentrator photovoltaic cells use lot of water for cooling mechanism which is major concern in desert areas. Further, the utilization of huge arrays of mirror or lenses greatly influence the ecological system of desert endangering the flora and fauna. In this context, perovskite cells are highly optimistic *w.r.t* cost and efficiency as it cost Rs 28 per Watt at peak performance for producing 19% efficiency. Moreover, its manufacturing process is simple & cost effective. Comparison of various solar cells *w.r.t* cost incurred per Watt at peak performance for producing specific efficiency is tabulated in Table 3.

4 Conclusion

As described in the preceding paragraphs, it has been concluded that recognition of solar cells depends on cost-efficacy, lifespan and efficiency. First generation solar cells have been undoubtedly the first choice of consumers due to their low cost and best available efficiency of 27.6% in spite of various researches on advanced solar cells of second generation and third generation. Further, cells of second generation have shown promise due to their low cost. In addition, these cells have cheaper synthesis process than the first generation cells. However, availability of raw materials has become an issue and lots of efforts are required to improve their efficiencies which is maximum 23.3% till date. It has been observed that while moving from first generation to second generation, efficiency of solar cell have decreased by 4.3%. Solar cells of third generation are the most advanced devices. Monocrystalline and polycrystalline Silicon are the raw materials that have been used in first generation solar cells while CdTe and CIGS have been utilized for second generation cells. While moving to third generation of solar cells; organic materials, perovskites and nano-sized Quantum Dots have been used. Subsequently, efficiency of solar cell has been increased by 11.5% while switching from first generation of solar cells to third generation. Although, commercialization of third generation solar cell is miles away due to degradation of the material in short span yet scientists are putting their best efforts for exploring advance techniques to eradicate the deficiency pertaining to commercialization of third generation solar cells.

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