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Review

Comparative analysis of photovoltaic technologies for high efficiency solar cell design

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ABSTRACT

Sun is the provenance of all kinds of energy prevailing on earth since ages. Being renewable and pollution free, solar energy has paved the way to compensate the exploitation of non-renewable sources of energy through the discovery of solar/photovoltaic cells. Considerable developments have been witnessed in solar cells with the passage of time which not only resulted in their compact sizes but also resulted in increased power conversion rate. This paper presents comparative analysis of photovoltaic through a detailed study of constructions, applications and efficiencies of the solar cells of third generation including their future trends and aspects. Among all types of solar cells, till date concentrated solar cells have shown maximum efficiency of 38.9%.

1. Introduction

A Solar/Photovoltaic (PV) cell is an electronic gadget which utilizes semiconductor materials to convert energy obtained from sun to electrical energy [1]. In this cell, flow of electrons take place when photons (energy packets) from sunlight get absorbed and electrons from the surface of semiconductor material are ejected, creating a hole which further gets occupied by the other electron. This whole process is termed as photovoltaic (PV) effect and this phenomena was firstly observed by a French physicist A. E. Becquerel in 1839 [2]. In PV cell, flow of electrons takes place in one direction and holes in opposite direction, which results in flow of current in the direction of holes. The absorbed electrons directly affect the total amount of current. Therefore, it is concluded that Photovoltaic/solar cells generate varying current depending upon the intensity of light [3].

The solar cells work on the following three aspects-

(i) Light absorption in order to generate holes and electrons.
(ii) Separation of holes and electrons.
(iii) Establishment of electric potential difference across p-n junction.

Working of solar cell due to PV effect is illustrated in Fig. 1.

World's first known Photovoltaic/Solar Cell was devised by Charles Fritts (USA) in 1883 using selenium coating over an ultra-thin layer of gold (Au). This solar cell was working on the phenomenon called photoconductivity and had an energy conversion efficiency of 1%. In the late 1940s, RS Ohl (USA) observed the production of unexpectedly large number of free electrons whenever a thin silicon wafer was exposed to the sunlight [4].The modern solar cell was firstly introduced to the world by the scientists of Bell Laboratories in

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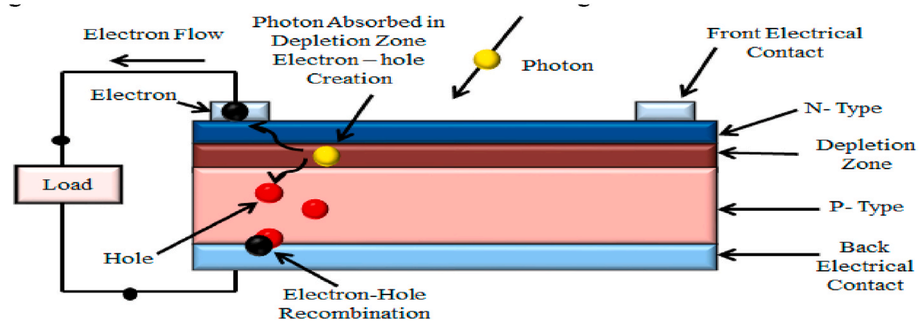

Fig. 1. PN junction Solar Cell.

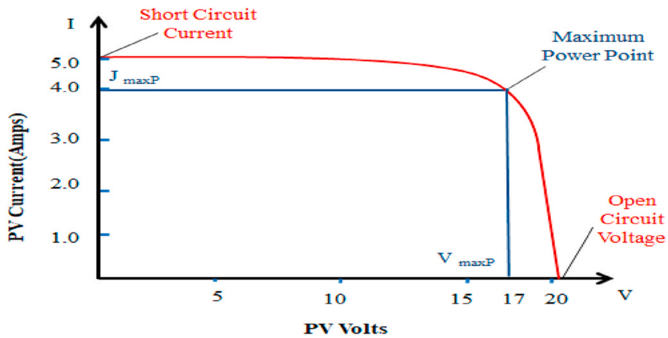

Fig. 2. Photovoltaic array voltage/current characteristic.

1954 [5]. These primitive solar cells initially had the efficiency of about 6% and the same was increased to 20% using single crystal Aluminium Gallium Arsenide ($Al_xGa_{1-x}As$) since AlGaAs has larger band gap, ranges between 1.42 and 2.16 eV. AlGaAs solar cells are more resistant to radiation in comparison to the primitive silicon solar cells [6]. In addition to increase in PCE of solar cell, it is required that solar cell must be non-toxic which is an essential factor for commercialization of solar cells. In this race, lead free perovskite solar cells (PSCs) are desirable candidates [7]. Presently, researchers are exploring new technologies and materials to embellish the ongoing research to attain environment friendly, economical and highly efficient solar cells. Among the recent researches, nanomaterials are the most promising contender [8]. Thus, aforementioned discoveries proved that, solar cells would sooner or later instigate the unlimited exploitation of solar energy in future without any pollution on earth.

Power conversion rate (η) of Solar cell is [9]-

$$\eta = \frac{Pout}{Pin} = \frac{\mathrm{FF} \times \mathrm{Voc} \times \mathrm{Jsc}}{\mathrm{Pin}}$$

where V_{OC} i.e. potential difference at infinite load resistance (Open Circuit Voltage), J_{SC} i.e. current through cell at zero load resistance (Short Circuited Current Density), Fill Factor (FF) i.e. ratio of the max. power,$P_{Mpp} = (V_{mp} \times J_{mp})$ generated by the cell and multiplication of V_{OC} & J_{SC}, P_{in} i.e. incident input power.

The same is graphically illustrated in Fig. 2.

The most common criteria for the materials which are used for solar cells as follows-

(i) High optical absorption.
(ii) Abundance of raw material.
(iii) Band gap ranging 1 eV–1.8 eV.
(iv) Low cost.
(v) High electrical conductivity.

Based on aforementioned criteria silicon, GaAs, CdTe and $CuInSe_2$ are the appropriate materials for construction of these cells.

Various advantages of Photovoltaic/solar cells are appended below-

(i) No pollution, no maintenance cost is associated.
(ii) Last for longer time.

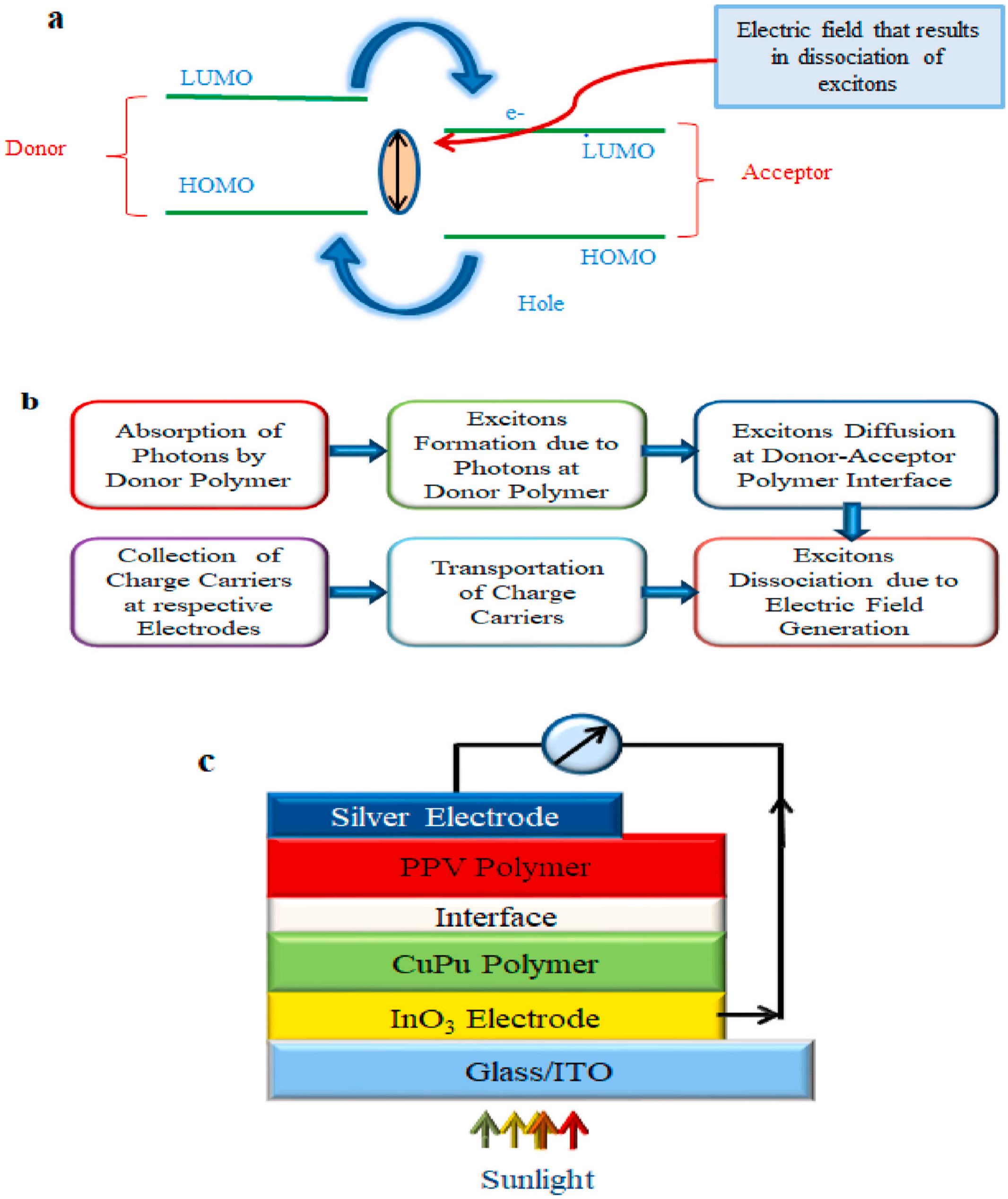

Fig. 3. **a** Breaking of excitons at donor and acceptor interface; **b** Steps during functioning of an OSC; and **c** Functioning of Organic PV/Solar Cells.

Table 1
Development of organic/Si solar cell from 2011 to 2020.

Sr. No.	Device Structure	Voc (V)	Jsc (mA per cm^2)	FF	Eff. (η) (%)	Year	Ref No.
1	Ag/PEDOT:PSS- Poly (3,4-ethylenedioxy-thiophene):poly(styrene sulfonate)/ P3HT/Si/Al	0.590	29.0	59.0	10.1	2011	[12]
2	Ag/MoO3/PEDOT:PSS/Si/Liq/Al	0.630	29.2	74.9	13.8	2014	[13]
3	Ti/Ag/PEDOT/c-Si/i,a-Si(H)/n,a-Si(H)/Al	0.630	36	70.3	15.8	2016	[14]
4	PEDOT:PSS + TEOS/MoOx/Ag/Si/Al	0.635	28.3	80	14.2	2018	[15]
5	Glass/ITO/Vox/PEDOT:PSS/SiNWs/Si/Al	0.541	45.4	58.3	14.4	2019	[16]
6	ITO/PEDOT:PSS/D18:Y6/PDIN/Ag	0.859	27.70	76.6	18.22	2020	[17]

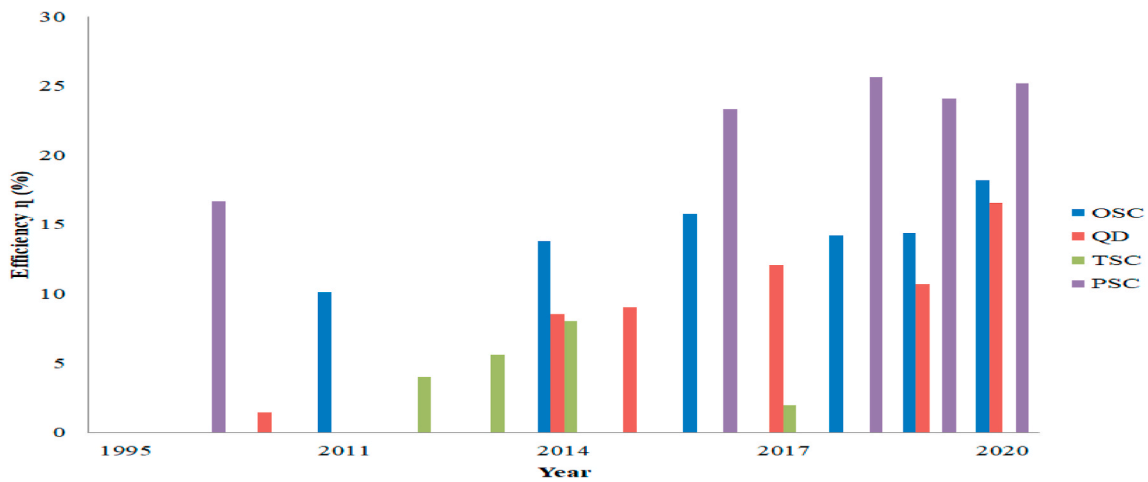

Fig. 4. Graph of improvements in efficiency of OSC, QD, TSC, PSC solar cell up to 2020.

Though solar cells have incredible advantages, they have some disadvantages too-

(i) They have high fitting cost and less efficiency.
(ii) Solar energy cannot be produced at cloudy and night time.

Various applications of solar cells are given below-

(i) They may be used to charge controllers, light meters.
(ii) They are used to power home appliances, gadgets and spacecraft.

2. Third generation solar cells (new emerging technologies)

Third generation solar cells possess the potential to outshine Shockley-Queisser limit (31%–41% efficiency) [10]. However, this technology is yet to be exploited commercially. Various types of third generation cells are described below-

2.1 Organic solar/PV cells (OSC)
2.2 Quantum dots (QD) solar/PV cells
2.3 Concentrated solar/PV cells (CPV)
2.4 Transparent solar/PV cells (TSC)
2.5 Perovskite solar/PV cells (PSC)

2.1. Organic Solar Cells (OSC)

Organic compounds mainly contain halogens, chalcogens and pnictogens alongwith carbon and hydrogen. Organic solar cells are named as these can either be synthesized using organic small molecules or polymers. These polymers were discovered by A. Heeger, A.

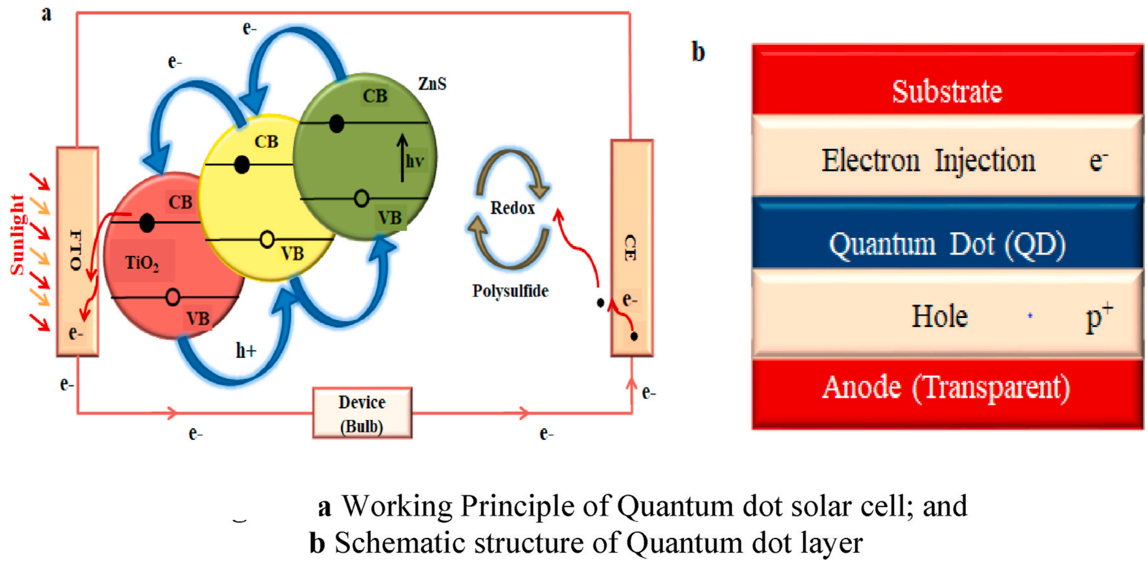

Fig. 5. **a** Working Principle of Quantum dot solar cell; and **b** Schematic structure of Quantum dot layer.

Table 2
Development of QD sensitized solar cells and their efficiencies from 2009 to 2020.

Sr. No.	Structure	Voc (V)	Jsc (mA per cm^2)	FF	Eff. (η) (%)	Year	Ref. No.
1	TiO2/PbS6/DPA/Spiro/Au	0.56	4.58	0.57	1.46	2009	[20]
2	ITO/Glass/ZnO/PbS-TBAI/PbS-EDT/Anode	0.5546	24.2	63.8	8.55	2014	[21]
3	TiO_2/QD (CdSeTe)/TiCl4	0.700	20.69	0.622	9.01	2015	[22]
4	Electrolyte-S^{2-}/S_x^{2-},QDs-ZCISe CE-N-MCd	0.765	25.21	0.626	12.07	2017	[23]
5	PbS CQDs configuration-ITO/ZnO/PbI2-capped PbSe (CQD)/PbS-EDT(1,2-ethanedithiol)/Au	0.573	28.1	66.3	10.68	2019	[24]
6	–	–	–	–	16.6	2020	[25]

Mac Diarmid and H. Shirakawa in 2000. These polymers are flexible and light weight and can be simply processed in laboratories. Organic polymers are made conducting by delocalizing π electrons upon doping of sulphur *e.g.* P3HT {poly(3-hexylthiophene-2,5-diyl)} acts as a donor while PCBM { [6,6]-Phenyl-C61-butyric acid methyl ester} acts as an acceptor [11].

Glass substrate is the starting layer in Bi-layer Organic Polymer Solar Cell, followed by Indium Oxide (InO_3) (TCO) which acts as anode. Further, donor polymer and acceptor polymer are sandwiched between InO_3 and silver (Ag) which acts as cathode. Donor polymer is a photoactive material as these have better absorption for light as compared to acceptor polymer. As light falls on glass substrate, it reaches to donor polymer where the photon is absorbed, resulting in formation of excitons instead of free electrons and holes. Excitons are produced because of low dielectric constant of donor and acceptor polymers. Exciton (an electron and a hole pair) are bound together by Coulombian force. Therefore, some external force is required to dissociate the excitons. These excitons move towards interface between donor-acceptor polymers and because of difference between Highest Occupied Molecular Orbitals (HOMO) and Lowest Un-occupied Molecular Orbitals (LUMO) of donor and acceptor polymers respectively, an electric field is generated which dissociates these excitons to free electrons and free holes which further get attracted by the respective electrodes. The same is illustrated in Fig. 3a [9,11]. Flow chart for working of Organic solar cell is illustrated in Fig. 3b.

In Fig. 3c shows the functioning of Organic PV/Solar Cells. Though, PCE of organic solar/PV cells has been uprisen tremendously for last thirteen years, these cells possess low life as these are degradable. Therefore, commercialization of these cells is difficult. The efficiency of these cells has been enhanced from 10.1% to 18.22% within 9 years i.e. 2011 [12] −2020 [17] which is illustrated in Table 1 and graphically shown in Fig. 4.

2.2. Nano crystal based or quantum dots (QD) based solar cells

Quantum dots in PV/solar cells were first hypothesized by Burnham and Duggan in 1990 with the motto of depreciation of energy losses utilizing semiconductors of varying band gaps. QDs are very small particles of a semiconductor of the order of few nanometers with size of Bohr radius. QDs are semiconductor nanostructure which is made mostly from transition metal groups. Working of quantum dot solar cell is explained through Fig. 5a [18].

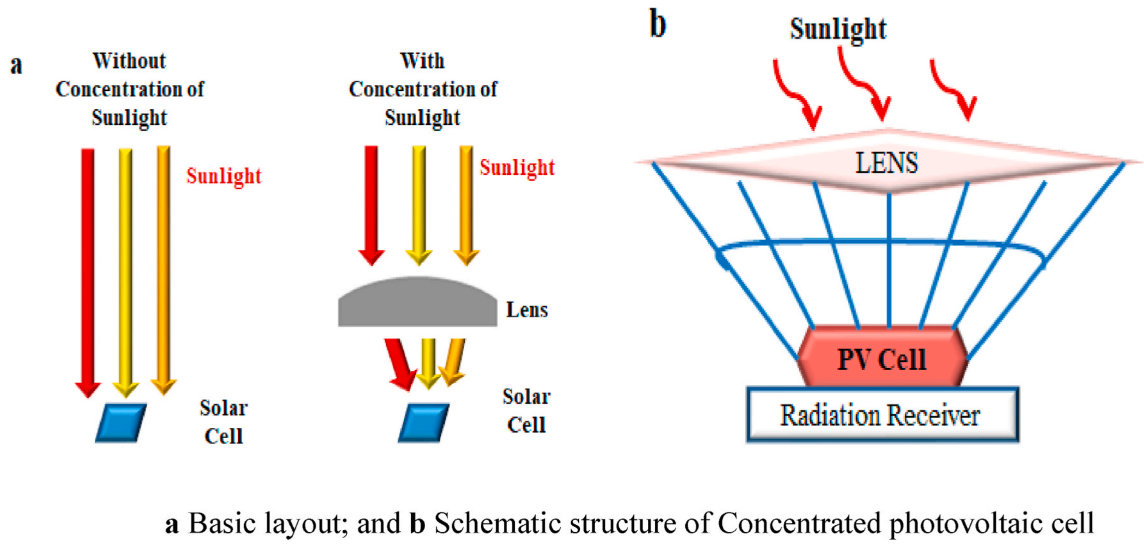

Fig. 6. **a** Basic layout; and **b** Schematic structure of Concentrated photovoltaic cell.

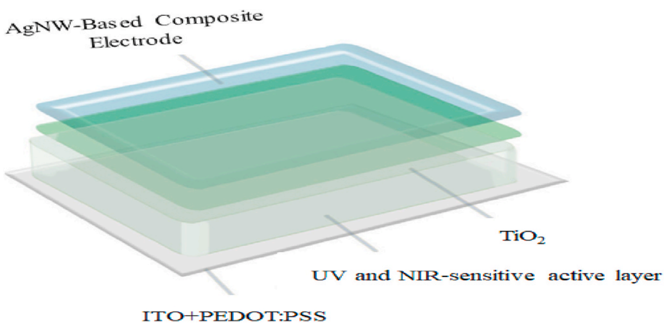

Fig. 7. Schematic architecture of transparent cell [32].

The formation of QD PV/solar cell constitutes sedimentation of skinny layer of ZnO settled by spin coating method, over glass substrates layered with Indium Tin Oxide (ITO). Then PbS quantum dots is deposited over ZnO layer. Further a layer of Molybdenum oxide (MoO_3) is deposited over PbS quantum dots layer. Finally the cell is completed by depositing gold using thermal evaporation in vacuum. The gold layer acts as an electrode [18].

Absorption of photons takes place in quantum dots and the free charged particles thus produced are deposited at positive and negative electrodes due to the internal electric field developed from the Fermi level alignment of two electrodes. Actual PCE of the QDSCs is measured nearly 2.5% against theoretical efficiency of 44% [19]. Schematic structure of quantum dot layer is illustrated through Fig. 5b [19]. The efficiency of QD has been enhanced from 1.46% to 16.6% within 11 years i.e. 2009 [20] - 2020 [25] which is illustrated in Table 2 and graphically shown in Fig. 4 [18].

2.3. Concentrated solar cells (CPV)

Concentrated photovoltaic (CPV) cell was introduced in 1970s [26]. Its technology involves principles of ray optics (assembling large concave mirrors and convex lenses to concentrate the sunlight over a small stretch of the solar cell) [27,28]. This results in generation of substantial amount of thermal energy by converging of sunlight radiations. Basic layout of this process is illustrated in Fig. 6a [29] and schematic structure is depicted in Fig. 6b [29]. This technology has shown promising nature. Depending upon the power of combination of mirrors and lenses, these cells are classified as low power concentrated solar cells, medium power concentrated solar cells and high power concentrated solar cells. CPVs have displayed the efficiency up to 38.9% [30]. These cells have numerous advantages such as absence of any moving parts, speedy response; operating cost is low and functions at ambient temperature.

Table 3
Development of transparent photovoltaic cells *w.r.t.* efficiencies from 2012 to 2020.

Sr. No.	Structure	Voc (V)	Jsc (mA per cm^2)	FF	Transmission (%)	Eff. (η) (%)	Year	Ref. No.
1	ITO/PEDOT:PSS/PBDTT-DPP:PCBM/TiO_2/AgNW	0.77	9.30	56.2	60 (at 550 nm)	4.0	2012	[34]
2	ITO/PEDOT/PTB7:PC71BM/BCP/thin Ag/1-D photonic crystal	0.733	10.9	70	28 Luminosity	5.6	2013	[35]
3	Graphene Mesh/PEDOT: PSS/PSEHTT/IC60BA/ZnO/ PEDOT: PSS/PBDTT-DPP:PC71BM/TiO_2/AgNW	1.62	7.62	64.2	45 Average 400–650 nm	8.02	2014	[36]
4	Standard inverted structure:polyacrylate (PA)/Cu NWs/ PEDOT:PSS/buffer layer/P3HT:PC61BM/MoO3/Ag	0.61	11.12	0.62	42 Avg. visible region200nm	4.23	2017	[37]

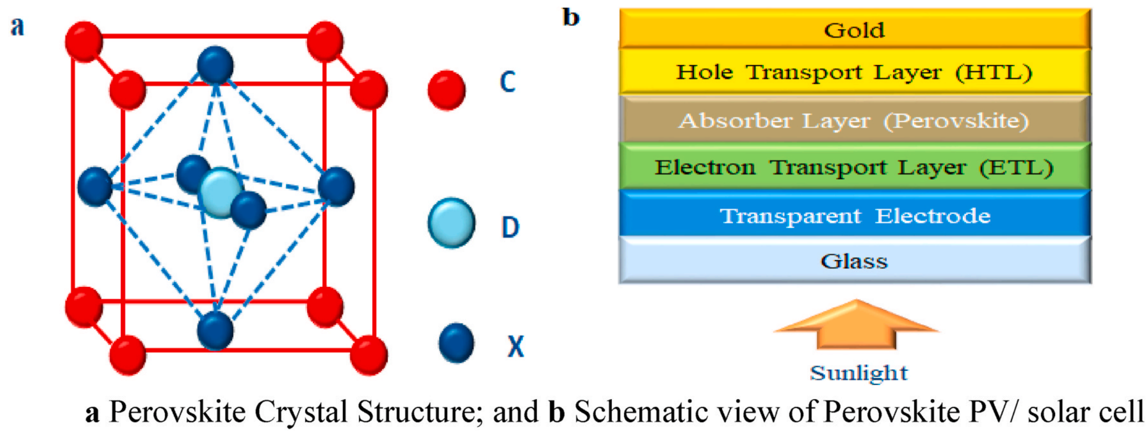

Fig. 8. **a** Perovskite Crystal Structure; and **b** Schematic view of Perovskite PV/solar cell.

2.4. Transparent solar cell (TSC)

The assurance of utilizing solar energy is restricted to rooftop panels and solar farms. In recent times, TSCs have grabbed the attention of researchers because of their optimistic/rising utilization in our day to day lives. If the usage of TSC with 90% glass on the surface of all buildings is made possible, then TSCs have the possibility to generate power equivalent to 40% of buildings' energy consumption. Nevertheless, TSCs are being utilized in vehicles and electronic equipment. USA, Germany, Japan and India have reported remarkable success with transparent PV/solar cell. The technology of transparent solar cell includes an FTO or ITO layered over glass substrate. Prior to stacking of any other materials, containing intrinsic losses of optical glass itself, thin films depreciate the transparency of cell to 80%–85%. Therefore, till date less than 80% transparency is achieved [31].

Fig. 7 illustrate the components of transparent solar cell (TSC) [32]. A light-sensitive film *w.r.t.* ultra violet (UV) and nearby Infra-red (NIR) is packed between two transparent electrodes. In this, electron donor is polymer hetero-junction (PBDTT-DPP poly(2, 60–4,8-bis(5-ethylhexylthienyl)benzo-[1,2-b; 3,4-b]dithiophene-alt-5-dibutyloctyl-3,6-bis(5-romothiophen-2-yl)pyrrolo[3,4-c]pyrrole-1, 4-dione))(active material) whereas electron acceptor is PCBM; and conjunction of both makes PBDTT-DPP: PCBM (proactive layer). 73% (nearly 550 nm) is the maximum transmission for photoactive material and 68% is an average transmission in the visible region (400–650 nm). However, UV and NIR regions strongly absorb light. As a modification, anode substrate i.e. ITO (Indium Tin oxide) layered with PEDOT: PSS is located as the lowermost film of TSC. As organic materials are sensitive, electrodes must be placed on the top however this may not withstand the film sedimentation process. To overcome this situation, AgNW (silver nano wire) is sprayed, forming a film over stacked substrate. AgNW is adhered to photoactive layer in presence of TiO_2 sol-gel solution. This stage requires minor processing [33]. From year 2012 [34], - 2014 [36] efficiency has been increased from 4% to 8.02% which is illustrated in Table 3 and graphically shown in Fig. 4 [31,37].

2.5. Perovskite based solar cell (PSC)

In 1839, Russian scientist LA Perovski had discovered calcium titanium oxide ($CaTiO_3$) which had a cubic crystal structure where bigger calcium cations were fixed at corners while smaller Titanium cation were located at body center and oxygen anions were face

Table 4
Development of perovskite PV/solar cells *w.r.t.* efficiencies from 2001 to 2020.

Sr. No.	Structure	Voc (V)	Jsc (mA per cm^2)	FF (%)	η (%)	Year	Ref. No.
1	HTL($CuInS_2$)/PA($MAPbI_3$-$CH_3NH_3PbI_3$)/ETL or Buffer layer (TiO_2)/FTO	0.881	23.26	81.57	16.72	2001	[42]
2	Glass/TCO/ETL(TiO_2)/$MASnI_3$($CH_3NH_3SnI_3$)/HTL(Spiro- OMeTAD)/metal	0.92	31.59	79.99	23.36	2016	[43]
3	Glass/TCO(SnO_2:F)/ETL(Cd_{1-x} Zn_x S)/defect layer 1/$MAPbI_3$-xClx/defect layer 2/HTL (CuI)/Back Contact Metal **Defect 1:**Interface b/w ETM/Absorber **Defect2:** Interface b/w absorber/HTM	1.21	25.33	84.11	25.68	2018	[44]
4	Glass/TCO (SnO_2: F)/ETL(TiO_2)/$MASnI_3$/HTL($CuSbS_2$)/Ag	0.936	31.7	81.1	24.1	2019	[45]
5	n-i-p planar-Au/HTL(CZTS-Cu_2ZnSnS_4)/$MAPbI_3$/ETL(TiO_2)/FTO	–	–	–	17.5	2020	[39]
6	–	–	–	–	25.2	2020	[25]

centered in the cube. All the material with chemical formula CDX_3 and crystallographic structure resembling $CaTiO_3$ are known as perovskites is illustrated in Fig. 8a [38]. In perovskites, C^+ represents MA (Methylammonium), FA(Formamidinium), Cs (Cesium), Rb (Rubidium), EA (Ethylammonium), GUA (Guanidinium), D^{2+} represents Cu (Copper), Mg (Magnesium), Eu (Europium), Yb (Ytterbium), Pb (Lead), Sn (Tin), Ge (Germanium) and X^- represents halogen anions. Some common perovskites are $CsSnI_3$, $CaTiO_3$ (Calcium Titanate), $CH_3NH_3PbI_3$ ($MAPbI_3$-Methylammonium lead halide), $CH_3NH_3SnI_3$ ($MASnI_3$), $CH(NH_2)_2PbI_3$ ($FAPbI_3$), $CH_3NH_3PbBr_3$ ($MAPbBr_3$) [39]. It was the first time in history when Miyasaka et al. in 2009 used artificial organometallic halides (perovskites) as photosensitizer instead of organic dye in a DSSC [40]. They used two different perovskites namely $MAPbI_3$ & $MAPbBr_3$ as photo sensitizer, mesoporous TiO_2 as electron transport medium (Photo anode) while LiI/I_2 in methyloxyacetonitrile (CH_3OCH_2CN) and $LiBr/Br_2$ in acetonitrile (CH_3CN) were used as electrolytes for MAPbI and MAPbBr respectively in two different DSSCs. These cells had very low efficiencies of 3.81% and 3.13% respectively and were not stable. Later, in 2012, first $MAPbT_3$ sensitized solar cells in solid form was developed by Gratzel et al. using spiro-OMeTAD (2,2′,7,7′-tetrakis-(*N,N*-di-*p*-methoxyphenyl-amine)-9,9′-spirobifluorene) as hole transport medium (HTM) in solid state [38]. This cell had shown the efficiency of 9.7%.

The primitive perovskite PV/solar was made on FTO coated glass substrates where this substrate is heat treated (annealed at 500 °C for 20 min) post deposition with compact layer TiO_2 by spin coating method. This compact layer performs as an Electron Transport Medium (ETM) and restricts hole movement. In addition, it acts as barrier between perovskite layer and FTO anode. Further, a mesoporous TiO_2 (m-TiO_2) layer was stacked up over compact layer of TiO_2 by doctor blading of nanocrystaline TiO_2 paste followed by heat treatment (sintered at 550 °C for 45 min). Then the resultant stack was coated with $MAPbI_3$ followed by heating for 10 min at around 100 °C. This results in the formation of $MAPbI_3$ nanocrystal over mesoporous TiO_2 layer. Thereafter, a layer of spiro-OMeTAD was deposited over $MAPbI_3$ by spin coating method [40]. This layer acts as hole transport medium (HTM). Finally, the cell formation was completed by deposition of gold (Au) layer using thermal evaporation. Schematic diagram of Perovskite PV/solar cell is illustrated in Fig. 8b.

Power converting rate of perovskite-based PV/solar cell has taken a major leap from 3.8% [41] to 25.2% between 2009 & 2020 [25]. Stability and durability of perovskite cells are major concern. Notwithstanding, being the most promising one, researches are discovering to manufacture perovskite cells with higher efficiencies having low cost. The efficiency improvement of perovskite solar cells starting from 2001 [37] with efficiency 16.72% has been enhanced up to 25.2% in 2020 [25] is illustrated in Table 4 and graphically shown in Fig. 4.

3. Conclusion

Popularity of PV/solar cells depends on three aspects - cost, availability of raw materials and efficiency. Third generation solar cell is the latest and most promising technology *w.r.t.* photovoltaic. Researches on the same are in progress. Among these, concentrated solar cell has shown 38.9% efficiency which not only is the highest among third generation solar cell but also shown the best efficiency among all solar cells. Further, perovskite solar cells have also shown unexpected results which could play major role in forthcoming years for running automobiles and other electronic equipment. This solar cell is more promising as it has shown an increase of efficiency from 3.13% to 25.2% within a period of 11 years i.e. 2009-2020. Comparison among different types of existing PV/solar cells of third generation is tabulated at Table 5. Best efficiency comparison of solar cells of third generation is illustrated graphically in Fig. 9. These cells are yet to be commercialized as the material degrades over a period of time, resulting in progressive depreciation in efficiency. Therefore, more efforts as well as exploration are required for commercialization of these cells.

Table 5
Comparison between different types of PV/solar Cells.

Cell Type		Best η (%)	η	Energy Band gap Eg (eV)	High Temp Performance/ Temp. coefficient	Size	Cost/ Levelized Cost of Energy	Materials/ Defect & Impurity	Fabrication Process	Merits	Demerits	Additional Details
Third Generation	**QD**	16.6	Very High/ tunable bandgap	~3	Stable		Less Expensive	Raw Material are Easy to find/may be defects	Easy	Versatile, tough	Demand of fixing period and area is high	Requires lesser installation time & large Space
	OSC	18.22		~2	Stable							Requires lesser installation time & small Space, Absorption Coefficient = 10^5 per cm
	CPV	38.9		–	Stable	Offers specialized range of product design				–	–	Requires greater installation time & large Space
	PSC	25.2		~1	Stable	Offers wide range of product design from flexible, light durable				Versatile, tough, more potency	Demand of Fixing period and area is high	Latest Technology, lesser installation time & minimum Space

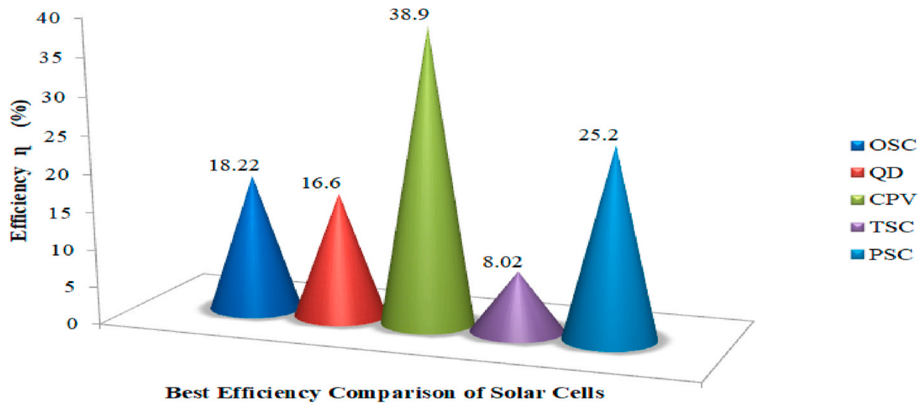

Fig. 9. Best efficiency comparison of Solar Cells.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] M.A. Green, Photovoltaics: technology overview, Energy Pol. 28 (14) (2000) 989–998.
[2] A.E. Becquerel, "Mémoire sur les effets électriques produits sous l'influence des rayons solaires", Comptes Rendus 9 (1939) 561–567.
[3] B. Srinivas, S. Balaji, M.N. Babu, Y.S. Reddy, Review on present and advance materials for solar cells, Int. J. Engg. Res. Onl. 3 (2015) 178–182.
[4] R.S. Ohl, "Light sensitive electric device", US Patent 240252, filed March 27 (1941).
[5] D.M. Chapin, C.S. Fuller, G.L. Pearson, A new silicon p-n junction photocell for converting solar radiation into electrical power, J. Appl. Phys. 25 (5) (1954) 676–677.
[6] L.M. Fraas, R.C. Knechtli, Design of high efficiency monolithic stacked multijunction solar cells, Proceedings of 13th IEEE Photovolt. Spec. Conf (1978) 886–891.
[7] S. Raghvendra, C. Pathak, S.K. Pandey, Design, performance, and defect density analysis of efficient eco-friendly perovskite solar cell, IEEE Trans. Electron. Dev. 67 (7) (2020) 2837–2843.
[8] S. Ananthakumar, J.R. Kumar, S.M. Babu (Eds.), Third-Generation Solar Cells: Concept, Materials and Performance - an Overview", Emerging Nanostructured Mater. For Energy and Environmental Sci. vol. 23, 2019, pp. 305–339.
[9] M. Wright, A. Uddin, Organic-inorganic hybrid solar cells: a comparative review, Sol. Energy Mater. Sol. Cell. 107 (2012) 87–111.
[10] Conibeer Gavin, Third generation photovoltaics, Mater. Today 10 (11) (2007) 42–50.
[11] O.A. Abdulrazzaq, V. Saini, S. Bourdo, E. Dervishi, A.S. Biris, Organic solar cells: a review of materials, limitations, and possibilities for improvement, Part. Sci. Technol. 31 (5) (2013) 427–442.
[12] S. Avasthi, S. Lee, Y.L. Loo, J.C. Sturm, Role of majority and minority carrier barriers silicon/organic hybrid heterojunction solar cells, Adv. Mater. 23 (48) (2011) 5762–5766.
[13] R. Liu, S.T. Lee, B. Sun, 13.8% efficiency hybrid Si/organic heterojunction solar cells with MoO_3 film as antireflection and inversion induced layer, Adv. Mater. 26 (34) (2014) 6007–6012.
[14] X. Zhang, D. Yang, Z. Yang, X. Guo, B. Liu, X. Ren, S. Liu, Improved PEDOT:PSS/c- Si hybrid solar cell using inverted structure and effective passivation, Sci. Rep. 6 (2016) 35091.
[15] Z. Xia, P. Gao, T. Sun, H. Wu, Y. Tan, T. Song, S.T. Lee, B. Sun, Buried MoO_x/Ag electrode enables high-efficiency organic/silicon heterojunction solar cells with a high fill factor, ACS Appl. Mater. Interfaces 10 (16) (2018) 13767–13773.
[16] C.Y. Chen, T.C. Wei, P.H. Hsiao, C.H. Hung, Vanadium oxide as transparent carrier-selective layer in silicon hybrid solar cells promoting photovoltaic performances, ACS Appl. Energy Mater. 2 (7) (2019) 4873–4881.
[17] Q. Liu, Y. Jiang, K. Jin, J. Qin, J. Xu, W. Li, J. Xiong, J. Liu, Z. Xiao, K. Sun, S. Yang, X. Zhang, L. Ding, 18% efficiency organic solar cells, Sci. Bull. 65 (4) (2020) 272–275.
[18] V.T. Chebrolu, H.J. Kim, Recent progress in quantum dot sensitized solar cells: an inclusive review of photoanode, sensitizer, electrolyte, and the counter electrode, J. Mater. Chem. C. 7 (11) (2019) 4911–4933.
[19] E.H.M. Sakho, O.S. Oluwafemi (Eds.), "Quantum Dots for Solar Cell Application", Nanomaterials for Solar Cell Applications, 2019, pp. 377–415.
[20] H. Lee, H.C. Leventis, S.J. Moon, P. Chen, S. Ito, S.A. Haque, T. Torres, F. Nueesch, T. Geiger, S.M. Zakeeruddin, M. Graetzel, M.K. Nazeeruddin, "PbS and CdS quantum dot-sensitized solid-state solar cells: old concepts, new results'', Adv. Funct. Mater. 19 (17) (2009) 2735–2742.
[21] C.H. Chuang, P.R. Brown, V. Bulovic, M.G. Bawendi, Improved performance and stability in quantum dot solar cells through band alignment engineering, Nat. Mater. 13 (8) (2014) 796–801.
[22] Z. Ren, J. Wang, Z. Pan, K. Zhao, H. Zhang, Y. Li, Y. Zhao, I.M. Sero, J. Bisquert, X. Zhong, Amorphous TiO2 buffer layer boosts efficiency of quantum dot sensitized solar cells to over 9%, Chem. Mater. 27 (24) (2015) 8398–8405.
[23] S. Jiao, J. Du, Z. Du, D. Long, W. Jiang, Z. Pan, Y. Li, X. Zhong, Nitrogen-doped mesoporous carbons as counter electrodes in quantum dot sensitized solar cells with a conversion efficiency exceeding 12%, J. Phys. Chem. Lett. 8 (3) (2017) 559–564.
[24] W. Ahmad, J. He, Z. Liu, K. Xu, Z. Chen, X. Yang, D. Li, Y. Xia, J. Zhang, C. Chen, Lead selenide (PbSe) colloidal quantum dot solar cells with >10% efficiency, Adv. Mater. 31 (33) (2019) 1900593.
[25] National Renewable Energy Laboratory, Best research-cell efficiencies. https://www.nrel.gov/pv/assets/images/best-research-cell-efficiencies.20200406.
[26] A.J. Nozik, Nanoscience and nanostructures for photovoltaics and solar fuels, Nano Lett. 10 (8) (2010) 2735–2741.
[27] P. Wurfel, U. Wurfel (Eds.), Physics of Solar Cells: from Basic Principles to Advanced Concepts, John Wiley & Sons, Hoboken, 2009.
[28] M. Bertolli (Ed.), "Solar Cell Materials", Course: Solid State II, Department of Physics, University of Tennessee, Knoxville, 2008.
[29] Takashi Kita, Yukihiro Harada, Shigeo Asahi (Eds.), "Energy Conversion Efficiency of Solar Cells", Green Energy and Tech, Springer, 2019, pp. 81–137.
[30] Freiburg, Photovoltaics report (pdf)", Fraunhofer ISE 14 (Nov 2019).

[31] P.R. Gomez, F. Pastorelli, P.M. Perez, M. Mariano, A.M. Otero, X. Elias, R. Betancur, J. Martorell, Semi-transparent polymer solar cells, J. Photon. Energy 5 (2015), 057212.
[32] A.A.F. Husain, W.Z.W. Hasan, S. Shafie, M.N. Hamidon, S.S. Pandey, A review of transparent solar photovoltaic technologies, Renew. Sustain. Energy Rev. 94 (2018) 779–791.
[33] S.G. Ullattil, P. Periyat, Sol-gel synthesis of titanium dioxide, Adv. In Sol-Gel Derived Materials & Technologies (2017) 271–283.
[34] C.C. Chen, L. Dou, R. Zhu, C.H. Chung, T.B. Song, Y.B. Zheng, S. Hawks, G. Li, P.S. Weiss, Y. Yang, Visibly transparent polymer solar cells produced by solution processing, ACS Nano 6 (8) (2012) 7185–7190.
[35] R. Betancur, P.R. Gomez, A.M. Otero, X. Elias, M. Maymo, J. Martorell, Transparent polymer solar cells employing a layered light-trapping architecture, Nat. Photon. 7 (12) (2013) 995–1000.
[36] A.R.b.M. Yusoff, L. Seungjoo, F.K. Shneider, W.J.D. Silva, J. Jang, High-performance semi-transparent tandem solar cell of 8.02% conversion efficiency with solution-processed graphene mesh and laminated Ag nanowire top electrodes, Adv. Energy Mater. 4 (12) (2014) 1301989.
[37] H. Zhai, Y. Li, L. Chen, X. Wang, L. Shi, R. Wang, J. Sun, Semi-transparent polymer solar cells with all-copper nanowire electrodes, Nano Res 11 (2018) 1956–1966.
[38] P. Kumar (Ed.), Handbook of Organic Solar Cells-Device Physics, Processing, Degradation, and Prevention, CRC Press, 2017, pp. 1–46.
[39] U. Syafiq, N. Ataollahi, P. Scardia, Progress in CZTS as hole transport layer in perovskite solar cell", Sol. Energy 196 (2020) 399–408.
[40] J. Zheng, M. Zhang, C.F.J. Lau, X. Deng, J. Kim, Q. Ma, C. Chen, M.A. Green, S. Huang, A.W.Y.H. Baillie, Spin-coating free fabrication for highly efficient perovskite solar cells, Sol. Energy Mater. Sol. Cells 168 (2017) 165–171.
[41] A. Kojima, K. Teshima, Y. Shirai, T. Miyasaka, Organometal halide perovskites as visible-light sensitizers for photovoltaic cells, J. Am. Chem. Soc. 131 (17) (2009) 6050–6051.
[42] D.O. Henderson, R. Mu, A. Ueda, M.H. Wu, E.M. Gordon, Y.S. Tung, M. Huang, J. Keay, L.C. Feldman, J.A. Hollingsworth, W.E. Buhro, Optical and structural characterization of copper indium disulfide thin films, Mater. Des. 22 (7) (2001) 585–589.
[43] H.J. Du, W.C. Wang, J.Z. Zhu, Device simulation of lead-free $CH_3NH_3SnI_3$ perovskite solar cells with high efficiency, Chin. Phys. B 25 (10) (2016) 108802.
[44] N. Thakur, R. Mehra, C. Devi, Efficient Design of perovskite solar cell using parametric grading of mixed halide perovskite and copper iodide, J. Electron. Mater. 47 (11) (2018) 6935–6942.
[45] C. Devi, R. Mehra, Device simulation of lead-free MASnI3 solar cell with $CuSbS_2$ (copper antimony sulfide), J. Mater. Sci. 54 (7) (2019) 5615–5624.

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