



Research Development and Future Aspects of Quantum dot and Perovskite Sensitized Solar Cells

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

The sustainable development of human depends upon the clever use of natural resources. In this regard the renewable energy resources are very important for our energy demand. Various research groups are working to develop efficient, economical, and practical solar energy harnessing devices. The use of solar cells is commercially encouraged worldwide. Although, silicon based solar cells are commonly in use but they have some draw backs associated to them regarding with cost and manufacturing processes. In the present time, Dye Sensitized Solar Cells (DSSC), Perovskite Sensitized Solar Cells (PSSCs) and Quantum Dot Solar Cells (QDSSC) are new techniques which

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have some advantages over silicon based solar cells. Although, there are some limitations also associated with them. The present paper deals with the historical context, present development, structural information, working mechanism, limitations, advantages and future research trends of quantum dot and perovskite sensitized solar cells.

Keywords: Graphene; quantum dots; perovskite; exciton; photovoltaic.

1. INTRODUCTION

As advances in optoelectronics, the researchers have been focused to develop efficient techniques and methods for trapping and conservation of solar energy. Starting from first generation solar cells involving silicon based solar cells, [1-3] second generation thin layer semiconductor based solar cells [4-6] and third generation solar cells [7-9] like DSSC (organic and inorganic as well as hybrid DSSC), perovskite solar cells [10-12] and quantum dot solar cells, [13-15] there is a long journey. The traditional semiconductor based solar cells have limitations. The photons having energy less than the band gap of semiconductor material cannot be absorbed and those who have higher energy can get thermalize to the band gap edge [16]. In this way, there is reduction in current and decrease in voltage respectively. The thermodynamic calculation of entire processes show that maximum efficiency obtained only up to 33% for normal semiconductor (with band gap 1.34eV) while it is up to 66% in quantum dot solar cells [17]. Although, at laboratory level it is low. The quantum dots have special feature to tune the band gap. Lead sulfide quantum dots can be used in the infrared frequencies also [18]. Manufacturing process of quantum dot solar cells is also simple and involve either manual or automatic spin coating or by roll printing [19]. Perovskite solar cells involve perovskite material in their structure. The lead or tin halide based perovskite with hybrid organic-inorganic nature solar cells are common [20]. Simple printing methods are used for their manufacture. At the laboratory level the efficiency reaches up to 25%. These cells are very light-weight and also useful in wireless electronic systems. This review is an effort to throw light on various aspects of the development of scientific view on molecular advanced material perovskite and nano-dimensional material [21] quantum dot, in the field of photo voltaics.

2. QUANTUM DOT SENSITIZED SOLAR CELLS (QDSSCs)

The use of nano dimensional advanced materials in the field of intelligent electronics [22], nonlinear

optics [23], photovoltaics, fluorescence sensing optoelectronics,[24,25] chemo therapy of cancer[26] etc. have been reported. In this part of the review we have focused our attention on the use of quantum dots in photovoltaic field. Quantum dots can be defined as nano sized material with narrow band gap. Therefore, they are important in the application of photovoltaic field as absorber in the visible region they can be used as replacement for dye in Gratzel's Dye sensitized solar cell[27]. Nowadays, researchers oriented towards the performance improvement in these QDSSCs. The scope of QDSSCs[28] are: (a) There are two electron hole pairs for each photon (b) QDs can also reduce the dark current and can improve the efficiency (c) Optical band gap of QDs is tunable. (d) The QDs have high value of extinction co-efficient. (e) Carrier multiplicates the impact of ionization show very high value of theoretical efficiency (44.4%). (f) Inorganic QDs like CdSe, CdTe, CdS and their alloyed compounds etc. are used as sensitizer, TiO₂ as one of the photoanode,[29] polysulfide redox mediator as electrolyte and noble metals, carbon based materials and metal chalcogenides are used for the construction of QDSSCs[30]. (g) The mechanism of photovoltaic function shown in Fig. 1 which is similar to the dye-sensitized solar cells. Due to 'quantum size effect' the quantum dot show characteristic properties which are different from the bulk materials. Historical background of photovoltaic cells starts since 1839, in which Edmond Becquerel built the first photo voltaic cell the historical events on photovoltaics can be summarized in the Table 1.

The principle of quantum dot solar cells is mainly based on quantum confinement [31]. The meaning of quantum confinement is the confining an exaction to the dimension smaller than it's Bohr radius (Exciton = Bound state of an electron-hole pair). The motivation of quantum dot solar cells is the multiple exciton generation (MEG), versatility and its reduced cost.

In quantum dot sensitized solar cells the phenomenon of multiple exciton generation(MEG) occurs in which a photon can generate multiple excitons and this is responsible for increase in

the efficiency of solar cell. MEG occurs only when the energy of photon is greater than band gap of a semiconductor. The photo excited excitons or carriers when undergo relaxation process they additional electron and hole pairs. Instead of heat evolution. Therefore the choice of better band gap materials is important in these cells.

2.1 Construction of QDSSCS

The construction of QDSSCs involve following steps:

- (i) Preparation of optically transparent electrode of appropriate size.
- (ii) Conductive compact layer deposition.
- (iii) Preparation of active layer.
- (iv) TiO₂ layer application.
- (v) Preparation of photo anode for the purpose of sensitization.
- (vi) Photo anode sensitization by using different quantum dot solution.
- (vii) Preparation of ZnS blocking layer.
- (viii) Counter electrode preparation with reduced grapheme oxide and copper. (Cu-RGO → Cu₂S- RGO)
- (ix) Assembling of over all solar cell.
- (x) Finally, the QSSCs testing is the last step of it's making.

2.2 Different Components of QDSSCs

i) Photo anode: It involves a wide band gap semiconductor layer, mostly TiO₂ [32]. It is notable that in QDs chalcogenides are used as sensitizer. The efficiency of QDSSC can be

tuned by use of better band gap species, CdS, CdSe, and CdTe (Table 2).

Lee et al reported an efficient quantum dot-sensitized solar cell based on co-sensitization of CdS/CdSe. Use of combination of quantum dot sensitizers for efficient redistribution and shifting of the band edge via "Fermi level alignment" has also been reported by the work of Mc Elory et al.[35] Highly efficient CdTe/CdS[36]. QDSSC fabrication by one-step linker assisted chemical bath deposition was reported by Yu and his co-workers[37]. For the increase in the efficiency of QDSSCs, the band gap tuning with size of QDs is important feature but it was observed that this may cause problem related with the stability of solar cell. Bailey et al[38] proposed the use of alloyed semiconductor quantum dots for tuning of optical property of QDSSCs without changing the particle size. Alloyed chalcogenides (Zn_xCd_{1-x}Te) have been reported to show 9-9.4%.

2.3 Passivation Layer

When we compare the performance of QDSSCs with the DSSCs, it was found the efficiency of QDSSCs is much lower than the DSSC.[39] This is due to the fact in photovoltaic mechanism the excited electron in quantum dots involve recombination process with redox mediator ions in the electrolyte which decreases the performance of QDSSCs.[40] The solution of this problem is the application of passivation layer am-TiO₂/ZnS/SiO₂ and ZnS layer as a passivation layer to the CdSeTe quantum dots to achieve 9.0 & 9.41 % efficiencies.

Table 1. Some historical events in solar cell research

Year	Discovery	Scientist
1839	First Voltaic cell	Edmond Becquerel
1839	Perovskite materials	Gustav Rose
1883	First solid state selenium Photo voltaic cell	Charles Fritis
1954	First practical photo voltaic cell	Bell Labs
1980	DSSC	M.Gratzell
1983	Quantum dots	Alexey Ekimov
1984	Colloidal Quantum dots	Louis Brus
1993	Colloidal CdX (X=S, Se, Te)	Louis Brus
2009	Quantum dot applications Perovskite solar cells	Tsutomu Miyasaka

Table 2. The chalcogenides with different band gaps

S. No.	Chalcogenide	Band Gap (eV)	Absorption (nm)
1	CdS[33]	2.3	~540
2	CdSe[33]	1.7	~T31
3	CdTe[34]	1.4	~887

2.4 Passivation Layer

Another disadvantage of QDSSCs are its toxicity Cd, Se, Te based quantum dot solar cells are lightly toxic and require stable polymers [41] Cd and Se ions have been known to use in core of quantum dots. Accumulation of quantum dots in kidney, spleen and liver is harmful. In UV and aqueous condition degradation may be enhanced.

2.5 Electrolyte in QDSSCs

Just like DSSC, in QDSSCs also involve the use of redox mediator for the purpose of conduction of electron from the photo anode to the counter electrode. Most commonly used electrolytes are S^{2-}/S_x^{2-} . Enhancement of V_{oc} and FF by the use of chemical additive as NaOH into polysulfide electrolyte was reported by Park and his co-workers.[42] To replace the liquid electrolyte due to leakage and easy vaporization the use of solid polymer electrolyte has been proposed by Duan and co-worker[43] in QDSSCs, but low ionic conductivity limits their performance. Again, gel polymer electrolyte (GPE) has been introduced and CdSe/CdS GPE based QDSSCs have been reported upto 45% efficiency.

2.6 Cathode

In QDSSC, the counter electrode of platinum is not suitable because of its reaction with sulfur and also it is non catalytic to sulfide in as well as it restrain charge transfer to polysulfide ions. The use of noble metal and chalcogenide are suitable for cathode in QDSSCs.[44]

2.7 Mechanism of QDSSCs

It involve the following steps:

1. Absorption of photons by quantum dots sensitized which are absorbed on the photo anode. This results in the excitation of electrons into its conduction band.
2. The electron from conduction band of sensitizer will be transferred to the conduction band of the semiconductor (TiO_2).
3. Again quantum dots receive electron from sulfide ions of electrolyte and regeneration occurs.
4. From conduction band of TiO_2/ZnO , electrons will be transferred to the external circuit and to the cathode. The schematic diagram of working mechanism of QDSSC is shown in Fig. 1.

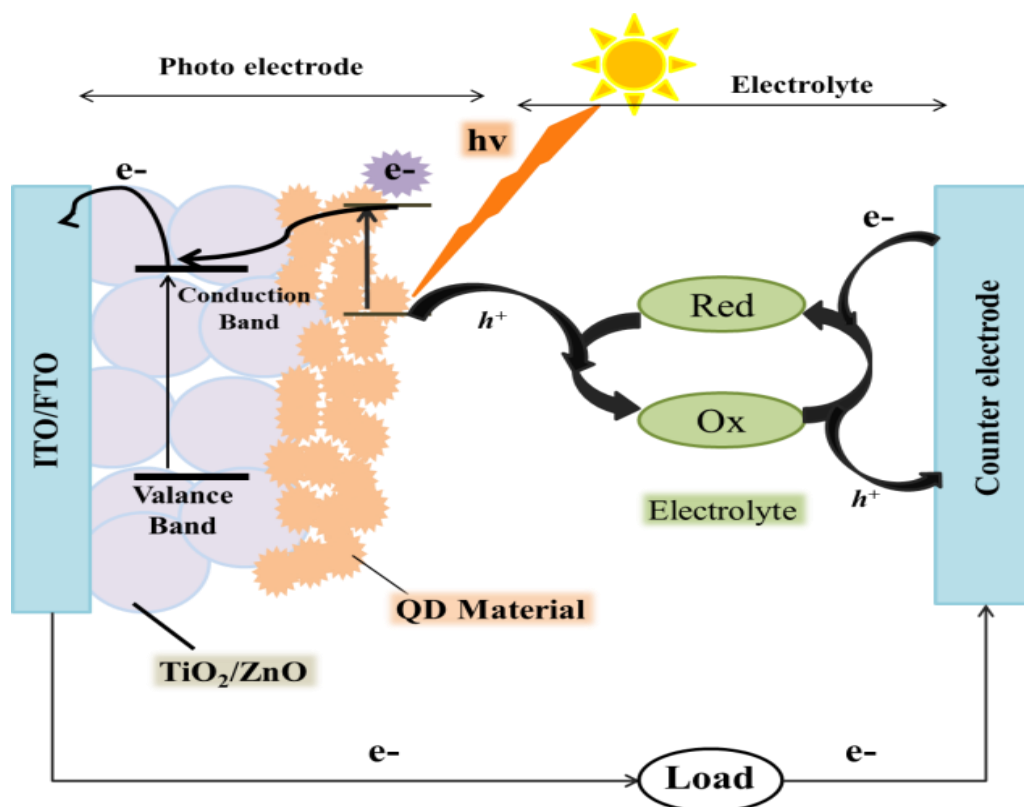


Fig. 1. Working Scheme of Quantum dot solar cell

3. PEROVSKITE SENSITIZED SOLAR CELLS

Perovskites are a class of materials that show a many fantastic properties like femo electric behavior, super conductivity, charge ordering, giant magnets resistance, catalytic properties and also optoelectronic properties. Metal halide perovskites act as semiconductor. Perovskite Solar cell(PSCs) has been invented as third generation photovoltaic technique. These solar cells have perovskite material as absorber of sun light. The general crystal structure can be represented for the perovskite is ABX_3 , where X is an anion and A and B are metal cations, which shown in Fig. 2(B).[45] A is large cation like ($CH_3CH_2NH_3^+$), formadinium ($NH_2CH=NH_2^+$) and ($CH_3NH_3^+$), B is cation metal of the carbon group of periodic table, i.e. Ge^{2+} , Sn^{2+} and Pb^{2+} and X is anion of halogen family.[46] The most commonly used perovskite in solar cell is $CH_3NH_3PbX_3$ (methyl ammonium lead halide), X may be chloride, bromide or iodide. The band gap energy for $CH_3NH_3PbX_3$ is in between 1.55-2.3 eV, which is near to the band gap range of single junction cell.[47]

The actual band gap of formamidinium lead halide ($H_2NCHNH_2PbX_3$) has some promising features like it's band gap can be tuned up to the value of 1.48 eV.[47] In these solar cells the exciton binding energy is small and separation of electrons and hole is easy. High absorption range of sun light also makes them more efficient for power generation.[48] In perovskite solar cells absorption coefficient is very high. The processing is very easy and material manufacturing cost is low. These cells can be

used for powering the wireless electronic applications.

The first perovskite reported in solar cell as dye is $CsSnI_3$ as a p-type hole transport layer and absorber[49] and the cell efficiency was 3.8% . Now, the efficiency of these cells has been achieved up to 25.7% in single junction cells.[50,51] Improvement the efficiency of perovskite solar cells involves optimizing various aspects of their design and materials. Like; material optimization, interface engineering, cell architecture etc.[52,53]

Shockley-Queasier limit define the theoretical efficiency of solar cell on 1.5G global spectra. The most common bandgap found to be 1.34eV with maximum conversion efficiency 33.7%. the single junction solar cell unable to achieve this theoretical efficiency but multi junction solar cell could be tuned the bandgap up to 1.3 eV .Reports are available with the $(FAPbI_3)_{1-x}(CsSnI_3)_x$ hybrid cell, which has a tunable bandgap energy (E_g) from 1.24 – 1.41 eV.[54]

3.1 Structure of Perovskite Sensitized Solar Cells

There are two main types of structure of perovskite are fabricated. These structures are planar structure and mesoporous structure. The planar architecture of perovskite cell further subdivided in to two categories: (a) Regular perovskite solar cell, (b) Inverted perovskite solar cell. In both the planar structure perovskite solar cell components are shown in Table 3. Both the structure are differs only as the position of ETL and HTL.[55]

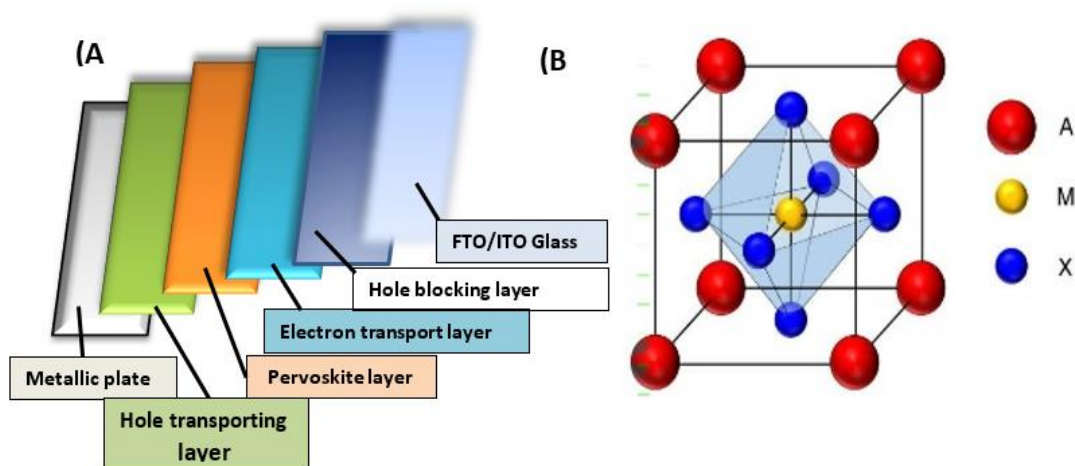


Fig. 2 (A). Layered Structure of Perovskite solar cell. (B) 3D Structure of AMX_3 perovskite

Table 3. The Components of planar Perovskite solar cell in top to bottom manner

Top to bottom order of components	Regular perovskite solar cell components	Inverted perovskite solar cell components
i.	Top electrode	Top electrode
ii.	Hole transport layer(HTL)	Electron transport layer(ETL)
iii.	Perovskite sensitizer	Perovskite sensitizer
iv.	Electron transport layer(ETL)	Hole transport layer(HTL)
v.	Bottom electrode	Bottom electrode
vi.	Transparent conductive Oxide/glass	Transparent conductive Oxide/glass

In the mesoporous structure, the main components of the cells are:

- (i) Transparent conducting oxide layer (TCO) as top electrode.
- (ii) Hole transport layer(HTL)
- (iii) Over the TCO substrate there is an oxide semiconductor compact layer of mesoporous metal oxide (TiO₂, Al₂O₃ etc.)[56]
- (iv) Perovskite sensitizer[57]
- (v) Electron transport layer
- (vi) Bottom electrode(commonly used metals are gold, silver and aluminium).

In Planar structure (Fig. 2(A)), the main component of the cell does not have mesoporous metal oxide layer but rest of the components are same as mesoporous structure cell.

Pradid and his co-workers discussed different types of carbon electrodes and structural details of perovskite solar cell. Different types of special mechanical and electrical properties of carbon material encourage researchers to replace metallic electrode by carbon based material. These electrode are more stable, chemically cheaper and easy for fabrication. These group of workers suggested the use of bio-carbon from biomass in the preparation of PSCs [58].

J.H. Park suggested conjugated polyelectrolyte as a semiconductive additive for the manufacture of stable and efficient perovskite cell[59]. Ze Yu and his team reported the use of transition metal complexes as p-type dopant in PSCs[60]. CsPb₂Br₃ assisted direct crystallization of the 3D perovskite phase for highly efficient and stable solar cell reported [61].

Lee et al have been reported organometallic halide planar structure perovskite solar cells with n-type TiO₂ CH₃NH₃PbI₃Cl and p-type spiro-O-MeTAD hole conductor [62]. The efficiency was

found to be increase from 7.6% to 10.9% by substitution of TiO₂ with Al₂O₃ in this cell. Proposed explanation was that injection of electron from conductor band of TiO₂ by the perovskite structure to the FTO electrode and in Al₂O₃ based cell, the perovskite layer behaves as absorber and as n-type component. It is essentially due to high range of band gap i.e.7-9 eV in case of Al₂O₃ [63]. Concluding remarks given as that the electron diffusion through perovskite is faster in TiO₂ and therefore it results an increase in efficiency of the cell. Heo et al[64] reported that structure where perovskite is filled up the pores to form a dense layer over the TiO₂ the perovskite functions as sensitizer and as a hole conductor, both.

3.2 Mechanism of Function for Perovskite Sensitized Solar Cells

Elgar et al reported mesoscopic CH₃NH₃PbI₃/TiO₂ heterojunction solar cells. The mechanism shown in Fig. 3 involve following steps:

1. In the first step the sensitizer CH₃NH₃PbI₃ absorbs the photons and produces excitons which get dissociated via electron injection at interface of sensitizer and semiconductor.
2. The second step involves migration of electron to FTO. In this step it travels through the TiO₂ network.
3. In the third and final step the electron reaches to the metal electrode. The efficiency of TiO₂/ CH₃NH₃PbI₃ cells was found to be 12%.

Islam and his co-workers[65] reported 15% efficiency for hybrid perovskite cell[66] of the type TiO₂ layer/ CH₃NH₃PbI₃/poly-triarylamine/A vapour u by blending TiO₂ nano particles with nano rods. Liu et al[67] reported the planner heterojunction perovskite solar cells by deposition method with 15.4% efficiency. Labana and coworker[68] in the same year published

their work on depleted hole conductor free lead halide iodide hetero junction solar cells and proposed that 8% efficiency. The increase was due to replacement of TiO₂ nano sheet with thinner planner perovskite solar cell using SnO₂ as compact layer and CuSeN as hole conductor.

3.3 Some Lead Free Perovskite Solar Cells:[69]

Due to poisonous property of lead, several research groups have been worked to replace lead by some eco-friendly material. In this effort the solar cell of the composition CH₃NH₃Pb_{1-x}l₃ have been reported which is partially substituted

by Sn in place of Pb. Other effort in this field is reported by Hao et al[70] with composition CH₃NH₃Sn_{0.25}Pb_{0.75}l₃ (n=7.37%) and CH₃NH₃Sn₃l₃(n=5.44%). Germanium (Ge²⁺) perovskite of the form, CsGeX₃ (X = Cl⁻, Br or I⁻) with efficiency 3.2%.

3.4 Limitations of Perovskite Solar Cells

1. Perovskite material is very much absorptive and moisture sensitive.
2. Stability and life-time of these cells is very low.
3. Use of lead which is poisonous in nature is also making it not eco-friendly.

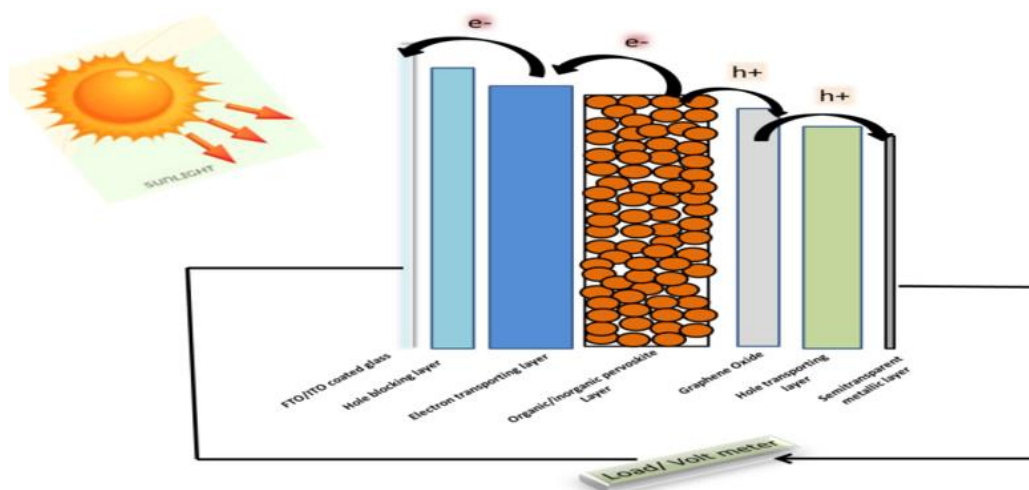


Fig. 3. Schematic mechanism of pervoskite solar cell

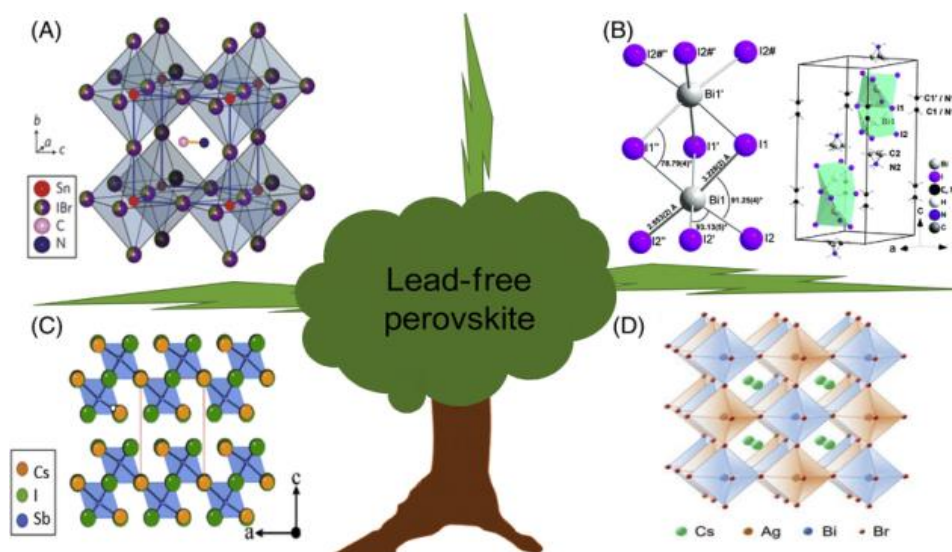


Fig. 4. Structures of Lead-Free Perovskites. (A) 3D crystal structure of CH₃NH₃SnI_{3-x}Br (B) 2D layered structure of Cs₃Sb₂I₉. (C) Local structure of the Bi₂I₉ 3-anion(left); cation and anion positions in the unit cell (right). (D) The crystal structure of Cs₂AgBiBr₆. [71]

3.5 Future Development of PSCs[72]

Efforts to remove the limitation of perovskite PSCs-

1. Research should be focused to improve the device stability.
2. Now, the application of graphene and its oxides have great considerable attention by research groups.
3. HTM (hole transport material/ETM (Electron Transport medium) layer not only could be replaced by graphene or its oxide but also could be inserted between perovskite and other HTM/ETM or between HTM/ETM and metal contact.
4. Wetting transparency property of 2D graphene the perovskite decomposition maybe released.
5. Graphene Oxide would add to the perovskite decomposition reactions and could improve.
6. The perovskite inserted tandem cells have been reported to show very high efficiency (26.7%).
7. Lead toxicity is a drawback of PSCs. Now, by the use of double perovskite (Elpasolites); with the general formula: $A_2BB'X_6$ type of the type $CS_2AgBiBr_6$ have been reported perovskite solar cell with these double perovskite also show material stability. In Fig. 4 some lead free perovskite structure are shown.
8. The application of Guanidinium thiocyanate (GuaSCN) to fine tune the mixture of tin and lead in the perovskite films to improve structural and opto electronic proportion have been reported the mixed tin-lead organic inorganic perovskite material with a small amount of GuaSCN show a low band gap, long charge carrier life time.
9. The perovskite silicon tandem Oxford PV reported world record for perovskite solar cell [73]. They have achieved a certified 28% conversion efficiency, which is the highest even performing single junction silicon solar cell validating the ability of perovskite to increase the performance of silicon based photovoltaics.

4. CONCLUSION

By the utilization of UV light spectrum of the solar energy using quantum dots now became a very progressive approach for the photovoltaic cell research. It has lots of possibilities in future in this field for the development of efficient sensitized solar cells.

Quantum dots band gap can be tuned by changing the size or composition. Processing of quantum dots can be done with the solution by roll to roll technique. QDSSC are helpful for less expensive manufacturing the commercialization of quantum dots is not easy, but in field of solar technology quantum dot solar cells will be an efficient and stable method for solar energy harvesting processes. This technology certainly will be one of the leaders in photovoltaic field and a promising game changes with a lots of possibilities in future.

Perovskite materials which are easily synthesized molecular materials have vibrant and versatile characteristics and they play vital role in vehicle batteries, sensors, lasers and micro-electronics. The perovskite photovoltaics have several advantages as comparison to silicon solar cells (a) Dancy carrier diffusion lengths (b) Widely-tuned band gap (1.5 eV to 2.3 eV); (c) great light absorption coefficient ($>10^4 \text{ cm}^{-1}$); (d) low cost and (e) easy fabrication. The vibrant increase in the efficiency of photovoltaic cells with low cost value make perovskite cells as a potential technique to achieve an efficient technology for green energy resource, to overcome the use of poisonous lead to the lead free perovskite cells are the attraction of researchers.

In this review quantum dot and perovskite solar cells are discussed for their structure, mechanism and applications. Starting with historical development to future prospects, advantages as well as limitations of both types of solar cell have been reviewed.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, Quillbot, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Al-Agel FA., Suleiman J, Khan SA. Studies on silicon quantum dots prepared at different working pressure. *Journal of Advance Research*. 2017;7:1128-1134. Available:<https://doi.org/10.1016/j.rinp.2017.03.002>
2. Płaczek-Popko E. Top PV market solar cells 2016. *Opto-Electronics Review*. 2017;25(2):55-64. Available:<https://doi.org/10.1016/j.opelre.2017.03.002>
3. Gianluca Timò, Calicchio M, Abagnale G, et al. Results on MOVPE SiGeSn deposition for the monolithic integration of III-V and IV elements in multi-junction solar cells. *Solar Energy Materials and Solar Cells/Solar Energy Materials and Solar Cells*. 2021;224:111016-111016. Available:<https://doi.org/10.1016/j.solmat.2021.111016>
4. Mohammad Bagher A. Types of Solar Cells and Application. *American Journal of Optics and Photonics*. 2015;3(5):94. Available:<https://doi.org/10.11648/j.ajop.20150305.17>
5. Singh BP, Goyal SK, Kumar P. Solar PV cell materials and technologies: Analyzing the recent developments. *Materials Today: Proceedings*. 2021;43:2843-2849. Available:<https://doi.org/10.1016/j.matpr.2021.01.003>
6. Khatibi A, Razi Astaraei F, Ahmadi MH. Generation and combination of the solar cells: A current model review. *Energy Science and Engineering*. 2019;7(2):305-322. Available:<https://doi.org/10.1002/ese3.292>
7. Mingsukang MA, Buraidah MH, Arof AK. Third-Generation-Sensitized Solar Cells. *Nanostructured Solar Cells*. Published Online; 2017. Available:<https://doi.org/10.5772/65290>
8. Mirabi E, Akrami Abarghuie F, Arazi R. Integration of buildings with third-generation photovoltaic solar cells: A review. *Clean Energy*. 2021;5(3):505-526. Available:<https://doi.org/10.1093/ce/zkab031>
9. Akinoglu BG, Tuncel B, Badescu V. Beyond 3rd generation solar cells and the full spectrum project. *Recent advances and new emerging solar cells*. *Sustainable Energy Technologies and Assessments*. 2021;46:101287. Available:<https://doi.org/10.1016/j.seta.2021.101287>
10. Correa-Baena JP, Saliba M, Buonassisi T, et al. Promises and challenges of perovskite solar cells. *Science*. 2017;358(6364):739-744. Available:<https://doi.org/10.1126/science.1252043>
11. Zuo C, Bolink HJ, Han H, Huang J, Cahen D, Ding L. Advances in Perovskite Solar Cells. *Advanced Science*. 2016;3(7):1500324. Available:<https://doi.org/10.1002/advs.201500324>
12. Bati ASR, Zhong YL, Burn PL, Nazeeruddin MK, Shaw PE, Batmunkh M. Next-generation applications for integrated perovskite solar cells. *Communications Materials*. 2023;4(1). Available:<https://doi.org/10.1038/s43246-022-00325-4>
13. Dias JA, Santagneli SH, Sidney, Younès Messaddeq. Perovskite Quantum Dot Solar Cells: An Overview of the Current Advances and Future Perspectives. *Solar RRL*. 2021;5(8). Available:<https://doi.org/10.1002/solr.202100205>
14. Ding Z, Li S, Jiang Y, Wang D, Yuan M. Open-circuit voltage loss in perovskite quantum dot solar cells. *Nanoscale*. 2023;15(8):3713-3729. Available:<https://doi.org/10.1039/d2nr06976h>
15. Hao M, Ding S, Sabah Gaznaghi, Cheng H, Wang L. Perovskite quantum dot solar cells: Current status and future outlook. *ACS energy letters*. Published Online. 2024:308-322. Available:<https://doi.org/10.1021/acsenerylett.3c01983>
16. Zhang H, Liu J, Xu T, Ji W, Zong X. Recent Advances on Small Band Gap Semiconductor Materials (≤ 2.1 eV) for Solar Water Splitting. *Catalysts*. 2023;13(4):728. Available:<https://doi.org/10.3390/catal13040728>
17. Markna JH, Rathod PK. Review on the efficiency of quantum dot sensitized solar cell: Insights into photoanodes and QD sensitizers. *Dyes and Pigments*. 2022;199:110094. Available:<https://doi.org/10.1016/j.dyepig.2022.110094>

18. Yun L, Ding C, Ding Y, et al. High-power mode-locked fiber laser using lead sulfide quantum dots saturable absorber. *Journal of Lightwave Technology*. 2022;40(24): 7901-7906.
Available:<https://doi.org/10.1109/jlt.2022.3206788>
19. Ma YF, Wang YM, Wen J, et al. Review of roll-to-roll fabrication techniques for colloidal quantum dot solar cells. *Journal of Electronic Science and Technology*. 2023;21(1):100189-100189.
Available:<https://doi.org/10.1016/j.jnlest.2023.100189>
20. Macdonald TJ, Lanzetta L, Liang X, Ding D, Haque SA. Engineering stable lead-free tin halide perovskite solar cells: Lessons from materials chemistry. *advanced materials*. Published Online. 2022;2206684.
Available:<https://doi.org/10.1002/adma.202206684>
21. Mousavi SM, Hashemi SA, Yari Kalashgrani M, Kurniawan D, Gholami A, Chiang WH. Bioresource-Functionalized quantum dots for energy generation and storage: Recent advances and feature perspective. *Nanomaterials*. 2022;12(21): 3905.
Available:<https://doi.org/10.3390/nano12213905>
22. Link to external site this link will open in a new tab. Intelligent materials and nanomaterials improving physical properties and control oriented on electronic implementations. ProQuest. Published Online 2023;3772.
Available:<https://doi.org/10.3390/electronic12183772>
23. Wu M, Tikhonov EV, Abudukadi Tudi, et al. Target-Driven design of deep-uv nonlinear optical materials via interpretable machine learning. *Advanced Materials*. 2023; 35(23).
Available:<https://doi.org/10.1002/adma.202300848>
24. Zhang S, Wei S, Liu Z, et al. The rise of AI optoelectronic sensors: From nanomaterial synthesis, device design to practical application. *Materials Today Physics*. 2022;27:100812.
Available:<https://doi.org/10.1016/j.mtphys.2022.100812>
25. Yang Z, Xu T, Li H, et al. Zero-Dimensional carbon nanomaterials for fluorescent sensing and imaging. *Chemical Reviews*. 2023;123(18):11047-11136.
Available:<https://doi.org/10.1021/acs.chemrev.3c00186>
26. Chugh V, Basu A, Kaushik A, Manshu, Bhansali S, Basu AK. Employing nano-enabled artificial intelligence (AI)-based smart technologies for prediction, screening, and detection of cancer. *Nanoscale*. 2024;16(11):5458-5486.
Available:<https://doi.org/10.1039/D3NR05648A>
27. Prakash P, Janarthanan Balasundaram, Al-Enizi AM, Mohd Ubaidullah, Sankapal BR. Effect of photovoltaic performance of plant-based cocktail DSSCs and adsorption of nano TiO₂ onto the solvent-influenced dye sensitizers. *Optical Materials*. 2022;133:113031-113031.
Available:<https://doi.org/10.1016/j.optmat.2022.113031>
28. Singh S, Khan ZH, Khan MB, Kumar P, Kumar P. Quantum dots-sensitized solar cells: A review on strategic developments. *Bulletin of Materials Science*. 2022;45(2).
Available:<https://doi.org/10.1007/s12034-022-02662-z>
29. Ansón- Casaos A, Martínez-Barón C, Angoy-Benabarre S, et al. Stability of a pyrimidine-based dye-sensitized TiO₂ photoanode in sacrificial electrolytes. *Journal of Electroanalytical Chemistry*. 2023;929:117114-117114.
Available:<https://doi.org/10.1016/j.jelechem.2022.117114>
30. Rasal AS, Lee T, Kao P, et al. Composition, morphology, and interface engineering of 3d cauliflower-like porous carbon-wrapped metal chalcogenides as advanced electrocatalysts for quantum dot-sensitized solar cells. *Small*. 2022;18(32).
Available:<https://doi.org/10.1002/smll.202202133>
31. Rasal AS, Yadav S, Kashale AA, Altaee A, Chang JY. Stability of quantum dot-sensitized solar cells: A review and prospects. *Nano Energy*. 2022;94:106854.
doi:<https://doi.org/10.1016/j.nanoen.2021.106854>
32. Mesoudy AE, Machon D, Ruediger A, et al. Band gap narrowing induced by oxygen vacancies in reactively sputtered TiO₂ thin films. *Thin Solid Films*. 2023;769: 139737.
Available:<https://doi.org/10.1016/j.tsf.2023.139737>
33. Lv W, Lei Y, Deng J, Fang J, Huang W. Zn-doped CdS/CdSe as efficient strategy to enhance the photovoltaic performance

- of quantum dot sensitized solar cells. *Solar Energy*. 2022;232:398-408.
Available:<https://doi.org/10.1016/j.solener.2022.01.006>
34. Asenjo M, Rovasio VA, Ma Belén Oviedo, Omar Linarez Pérez, Iglesias RA. Nanotubular TiO₂ films sensitized with CdTe quantum dots: Stability and adsorption distribution. *Chemical physics*. 2024;579:112196-112196.
Available:<https://doi.org/10.1016/j.chemphys.2024.112196>
 35. McElroy N, Page RC, Espinbarro-Valazquez D, et al. Comparison of solar cells sensitised by CdTe/CdSe and CdSe/CdTe core/shell colloidal quantum dots with and without a CdS outer layer. *Thin Solid Films*. 2014;560:65-70.
Available:<https://doi.org/10.1016/j.tsf.2013.10.085>
 36. Liao D, Liang G, Liu Y, et al. Design an efficient photo electrochemical aptasensor for PCB72 based on CdTe@CdS core@shell quantum dots-decorated TiO₂ nanotubes. *Journal of hazardous materials*. 2023;441:129901-129901.
Available:<https://doi.org/10.1016/j.jhazmat.2022.129901>
 37. Yu Z, Zhang Q, Qin D, et al. Highly efficient quasi-solid-state quantum-dot-sensitized solar cell based on hydrogel electrolytes. *Electrochemistry Communications*. 2010;12(12):1776-1779.
Available:<https://doi.org/10.1016/j.elecom.2010.10.022>
 38. Bailey RE, Nie S. Alloyed Semiconductor quantum dots: Tuning the optical properties without changing the particle size. *Journal of the American Chemical Society*. 2003;125(23):7100-7106.
Available:<https://doi.org/10.1021/ja035000o>
 39. B.B. Dumre, Ellingson RJ, Khare SV. Effects of short-range order on phase equilibria and opto-electronic properties of ternary alloy Zn_xCd_{1-x}Te. *Solar Energy Materials and Solar cells/Solar energy Materials and Solar Cells*. 2022;248:111971-111971.
Available:<https://doi.org/10.1016/j.solmat.2022.111971>
 40. Jassby D, Farner Budarz J, Wiesner M. Impact of aggregate size and structure on the photocatalytic properties of TiO₂ and ZnO Nanoparticles. *Environmental Science and Technology*. 2012;46(13):6934-6941.
Available:<https://doi.org/10.1021/es202009h>
 41. Rahman MM, Karim MR, Alharbi HF, Aldokhayel B, Uzzaman T, Zahir H. Cadmium selenide quantum dots for solar cell applications: A review. *Chemistry – An Asian Journal*. 2021;16(8):902-921.
Available:<https://doi.org/10.1002/asia.202001369>
 42. Park S, Son MK, Kim SK, Jeong MS, Prabakar K, Kim HJ. The effects of electrolyte additives on the cell performances of CdS/CdSe quantum dot sensitized solar cells. *Korean Journal of Chemical Engineering*. 2013;30(11):2088-2092.
Available:<https://doi.org/10.1007/s11814-013-0195-4>
 43. Duan J, Tang Q, Sun Y, He B, Chen H. Solid-state electrolytes from polysulfide integrated polyvinylpyrrolidone for quantum dot-sensitized solar cells. *RSC Adv*. 2014;4(105):60478-60483.
Available:<https://doi.org/10.1039/c4ra10764k>
 44. Layla Haythoor Kharboot, Nor Akmal Fadil, Asma T, Sani A, Norhuda Hidayah Nordin, Ghazali H. A Review of transition metal sulfides as counter electrodes for dye-sensitized and quantum dot-sensitized solar cells. *Materials*. 2023;16(7):2881-2881.
Available:<https://doi.org/10.3390/ma16072881>
 45. Park NG. Perovskite solar cells: An emerging photovoltaic technology. *Materials Today*. 2015;18(2):65-72.
Available:<https://doi.org/10.1016/j.mattod.2014.07.007>
 46. Valadi K, Gharibi S, Taheri-Ledari R, Akin S, Maleki A, Shalan AE. Metal oxide electron transport materials for perovskite solar cells: A review. *Environmental Chemistry Letters*. 2021;19(3):2185-2207.
Available:<https://doi.org/10.1007/s10311-020-01171-x>
 47. Eperon GE, Stranks SD, Menelaou C, Johnston MB, Herz LM, Snaith HJ. Formamidinium lead trihalide: A broadly tunable perovskite for efficient planar heterojunction solar cells. *Energy and Environmental Science*. 2014;7(3):982.
Available:<https://doi.org/10.1039/c3ee43822h>
 48. Min H, Lee DY, Kim J, et al. Perovskite solar cells with atomically coherent interlayers on SnO₂ electrodes. *Nature*. 2021;598(7881):444-450.

- Available:<https://doi.org/10.1038/s41586-021-03964-8>
49. Chung I, Lee B, He J, Chang RPH, Kanatzidis MG. All-solid-state dye-sensitized solar cells with high efficiency. *Nature*. 2012;485(7399):486-489. Available:<https://doi.org/10.1038/nature11067>
 50. Green MA, Dunlop ED, Masahiro Yoshita, et al. Solar cell efficiency tables (version 62). Published Online; 2023. Available:<https://doi.org/10.1002/pip.3726>
 51. Energie HZB für M und. Weltrekord wieder beim HZB: Fast 30 % Wirkungsgrad bei Tandemsolarzellen der nächsten Generation. HZB Website. Available:https://www.helmholtz-berlin.de/pubbin/news_seite?nid=23248
 52. Naveen Kumar Elangovan, Raju Kannadasan, B.B. Beenarani, Alsharif MH, Kim MK, Z. Hasan Inamul. Recent developments in perovskite materials, fabrication techniques, band gap engineering, and the stability of perovskite solar cells. *Energy Reports*. 2024;11:1171-1190. Available:<https://doi.org/10.1016/j.egy.2023.12.068>
 53. Wu Z, Bi E, Ono LK, et al. Passivation strategies for enhancing device performance of perovskite solar cells. *Nano Energy*. 2023;115:108731-108731. Available:<https://doi.org/10.1016/j.nanoen.2023.108731>
 54. Soonmin H, Hardani, Nandi P, Mwankemwa BS, Malevu TD, Malik MI. Overview on different types of solar cells: An update. *Applied Sciences*. 2023;13(4):2051. Available:<https://doi.org/10.3390/app13042051>
 55. Wang P, Guo Y, Yuan S, et al. Advances in the structure and materials of perovskite solar cells. *Research on Chemical Intermediates*. 2015;42(2):625-639. Available:<https://doi.org/10.1007/s11164-015-2046-x>
 56. Sullivan CM, Nienhaus L. Generating spin-triplet states at the bulk perovskite/organic interface for photon upconversion. *Nanoscale*. 2023;15(3):998-1013. Available:<https://doi.org/10.1039/d2nr05767k>
 57. Preawpun Pradid, Kanyanee Sanglee, Non Thongprong, Surawut Chuangchote. Carbon Electrodes in Perovskite Photovoltaics. *Materials*. 2021;14(20):5989-5989. Available:<https://doi.org/10.3390/ma14205989>
 58. Jong Hyun Park, Young Wook Noh, Jung Min Ha, et al. Anionic conjugated polyelectrolyte as a semiconducting additive for efficient and stable perovskite solar cells. *ACS Applied Materials and Interfaces*. Published Online; 2023. Available:<https://doi.org/10.1021/acsami.3c12878>
 59. Yu Z, Hagfeldt A, Sun L. The application of transition metal complexes in hole-transporting layers for perovskite solar cells: Recent progress and future perspectives. *Coordination Chemistry Reviews*. 2020;406:213143. Available:<https://doi.org/10.1016/j.ccr.2019.213143>
 60. Gao C, GAO K, Zhang B, et al. CsPb₂Br₅ assisted direct crystallization of 3D perovskite phase for highly efficient and stable solar cells. *Energy and Environmental Science*. Published Online; 2024. Available:<https://doi.org/10.1039/d4ee00229f>
 61. Zhang J, Shang M, Wang P, et al. n-Type doping and energy states tuning in CH₃NH₃Pb_{1-x}Sb_{2x/3} Perovskite Solar Cells. *ACS Energy Letters*. 2016;1(3):535-541. Available:<https://doi.org/10.1021/acsenergylett.6b00241>
 62. Ma L, Liu P, Wu X, et al. Investigation of organic-inorganic hybrid perovskite solar cells based on Al₂O₃ nanorods. *Solar energy*. 2017;153:77-82. Available:<https://doi.org/10.1016/j.solener.2017.05.062>
 63. Heo JH, Im SH, Noh JH, et al. Efficient inorganic-organic hybrid heterojunction solar cells containing perovskite compound and polymeric hole conductors. *Nature Photonics*. 2013;7(6):486-491. Available:<https://doi.org/10.1038/nphoton.2013.80>
 64. Islam N, Yang M, Zhu K, Fan Z. Mesoporous scaffolds based on TiO₂ nanorods and nanoparticles for efficient hybrid perovskite solar cells. *Journal of materials chemistry A*. 2015;3(48):24315-24321. Available:<https://doi.org/10.1039/c5ta06727h>
 65. Islam A, Li J, Pervaiz M, et al. Zwitterions for organic/perovskite solar cells, light-emitting devices, and lithium ion batteries:

- Recent progress and perspectives. *Advanced Energy Materials*. 2019;9(10): 1803354-1803354.
Available:<https://doi.org/10.1002/aenm.201803354>
66. Liu M, Johnston MB, Snaith HJ. Efficient planar heterojunction perovskite solar cells by vapour deposition. *Nature*. 2013;501(7467):395-398.
Available:<https://doi.org/10.1038/nature12509>
67. Laban WA, Etgar L. Depleted hole conductor-free lead halide iodide heterojunction solar cells. *Energy and Environmental Science*. 2013;6(11):3249.
Available:<https://doi.org/10.1039/c3ee42282h>
68. Ke W, Kanatzidis MG. Prospects for low-toxicity lead-free perovskite solar cells. *Nature Communications*. 2019;10(1).
Available:<https://doi.org/10.1038/s41467-019-08918-3>
69. Hao F, Stoumpos CC, Chang RPH, Kanatzidis MG. Anomalous band gap behavior in mixed sn and pb perovskites enables broadening of absorption spectrum in solar cells. *Journal of the American Chemical Society*. 2014;136(22): 8094-8099.
Available:<https://doi.org/10.1021/ja5033259>
70. Wang R, Wang J, Tan S, Duan Y, Wang ZK, Yang Y. Opportunities and challenges of lead-free perovskite optoelectronic devices. *Trends in Chemistry*. 2019; 1(4):368-379.
Available:<https://doi.org/10.1016/j.trechm.2019.04.004>
71. Cheng N, Li W, Zhang M, et al. Enhance the performance and stability of methylammonium lead iodide perovskite solar cells with guanidinium thiocyanate additive. *Current Applied Physics*. 2019;19(1):25-30.
Available:<https://doi.org/10.1016/j.cap.2018.10.020>
72. Nazir G, Lee S, Jong Hoon Lee, et al. Stabilization of perovskite solar cells: Recent developments and future perspectives. *Advanced Materials*. 2022;34(50).
Available:<https://doi.org/10.1002/adma.202204380>
73. Messmer C, Goraya BS, Nold S, et al. The race for the best silicon bottom cell: Efficiency and cost evaluation of perovskite–silicon tandem solar cells. *Progress in Photovoltaics: Research and Applications*. Published Online; 2020.
Available:<https://doi.org/10.1002/pip.3372>

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