

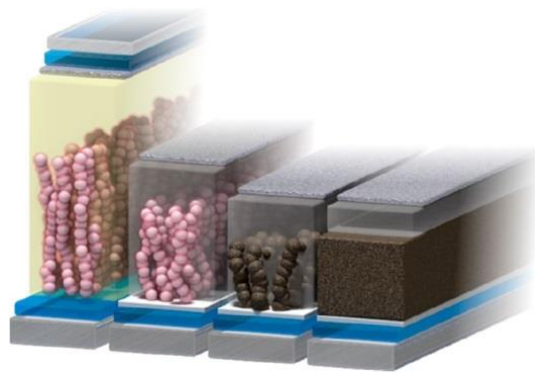
Perovskite Solar Cells

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Abstract

In recent years, world of photovoltaic cells has witnessed rapid evolution by highly efficient solid-state hybrid solar cells based on organic-inorganic halide perovskites. Performance of these perovskite solar cells has rapidly surpassed that of both conventional dye-sensitized and organic photovoltaics. In this research, remarkable achievements in solar cells containing perovskite in distinct mesoporous and thin-film device architectures are reviewed and notable attributes of different kinds of perovskites are described. The main steps leading to evolutionary paths of photovoltaic technology with perovskites and obstacles on the way toward commercialization and development of these photovoltaic systems are discussed and the expected future of this advancing field is taken under consideration.



Keywords:

Hybrid organic-inorganic halide perovskite, photovoltaics, energy conversion, charge transport

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Introduction

Sunlight with less harmful impact on the environment, has been considered as the most clean, abundant and reliable source of energy. With the aim of conversion of sunlight energy to electricity, photovoltaic systems have become increasingly attractive and scientifically demanding field of research in order to reach high energy conversion efficiency with low processing costs. These goals have been followed by applying distinct photoactive materials and different fabrication methods.

Silicon has been one of the favored materials in microelectronics and photovoltaic systems, which brought efficiencies of single crystal silicon solar cells close to 25%. These crystalline silicon solar cells have made considerable advances over decades, introducing them as an appropriate source for electricity generation instead of fossil fuels. On the other hand, organic materials in thin film solar cells reached photoconversion efficiency of 11%¹. However, recent investigations on combination of organic and inorganic materials in perovskite structures have shown potentiality of these solution-processable semiconductors for easy low-cost fabrication of high-efficient solar cells².

In the last 10 years, third generation of photovoltaic systems have drawn special attention to themselves as they have shown very considerable progress in stability and efficiency. It is predictable that in the upcoming years, the main attitude of researches will follow the directions toward solving ambiguities that are still remaining about perovskite structures and their properties and special efforts will be done to reach highest efficiencies while retaining low-cost fabrication techniques.

Properties and photovoltaic interests of perovskites

Over recent decades, the optical and electronic properties of perovskite materials have been studied. Perovskite, described by ABX_3 structure, consists of organic components in cuboctahedral A site and inorganic components in octahedral B site, which can be easily synthesized and is structurally and compositionally flexible (Figure1)³. Different proportions of organic cations (methylammonium, ethylammonium), inorganic cations (Pb, Sn) and halide anions (I, Br, Cl) can be incorporated in mixed perovskites and have made tuning of features of these structures feasible⁴. Therefore, hundreds of structures have been composed with distinct properties, i.e. insulating, semiconducting, conducting, superconducting, optoelectronic, piezoelectric, antiferromagnetic, etc. Perovskites are the archetypal systems for phase transitions with accessible cubic, tetragonal, orthorhombic, trigonal, and monoclinic polymorphs depending on the tilting and rotation of the BX_6 polyhedra in the lattice³.

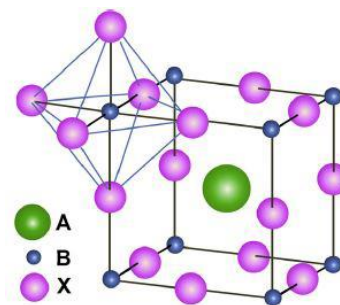


Figure 1. Perovskite crystal structure, X is an anion and A and B are cations³

Outstanding performance of perovskites origins from the strong optical absorption⁵ and low non-radiative carrier recombination rates in these structures. Absorption measurements have shown that perovskite has direct bandgap⁶ with high extinction coefficient⁷. Its considerably high light absorption, has led to reduction of the

required thickness of the perovskite layer. As transport of photogenerated charge carriers is much easier in thin layers, charge collection is less challenging in the photovoltaic systems based on thin layers of perovskite. Moreover, Perovskites are found as structures with high charge carrier mobility and life time, valuable properties for photovoltaic applications. These photovoltaic properties of organometal perovskite structures have been determined by fabrication of light emitting diodes (LED) which revealed strong excitonic features of these structures⁸.

Investigations on photon absorption of perovskites, have demonstrated relatively high exciton binding energy for these structures. Excitonic binding energy has been estimated around 37-50meV for iodide⁹ perovskites at low temperature and binding energies around 35-75meV have been reported¹⁰ for mixed chloride ones at room temperature. This amount of binding energy that is higher than that of III-V semiconductors with similar bandgap, lowers the absorption threshold and increases the ability for generation of unbound electron-hole pairs resulting from above-bandgap absorption. This absorption of photons with energies more than bandgap energy is comparable and even higher than that in many direct-bandgap III-V semiconductors, such as GaAs. However, this absorption is still lower than that of some inorganic chalcogenides.

Density functional theory (DFT) calculations have shown that the bandgap of hybrid perovskites is dominated by a giant spin-orbit coupling (SOC) in the conduction band⁶. These calculations predicted reversed ordering of band-edge as compared to tetrahedrally bonded semiconductors. It seems that this reverse ordering of band-edge states in perovskite, results in splitting in the conduction band (specifically for a p-like conduction band),

rather than in the valence band. Spin-orbit split-off band related to the triply degenerated conduction band of the cubic lattice, without spin-orbit coupling, makes direct and isotropic transitions possible. However, due to the strong spin-orbit coupling, the electronic states involved in the optical absorption are slightly perturbed by local distortions of the lattice. The major role of spin-orbit coupling is significant reduction of the bandgap by introducing a large splitting of the first degenerated conduction levels. Figure 2 clearly illustrates the effect of spin-orbit coupling interaction in electronic band structure of $CH_3NH_3PbBr_3$. As the result of reverse band-edge ordering, the bandgap increases with increasing temperature for any given phase of perovskites⁶. Therefore, Temperature has considerable influence on the size of bandgap.

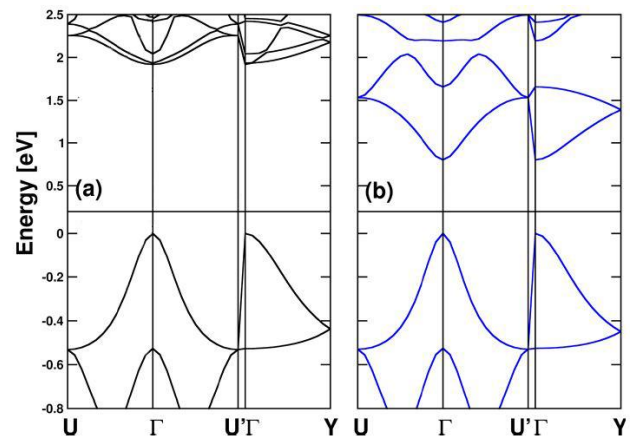


Figure 2. Electronic band structure of $CH_3NH_3PbBr_3$, without (a) and with (b) spin-orbit coupling interaction⁶

Temperature also matters for fabrication processes. It is observed that low temperature procedures have had better results because of decomposition of perovskites before reaching their melting point¹¹. For characterization of the deposited perovskite layer for cell fabrication process, XRD measurements can reveal information about grain size and defects. Narrow x-ray diffraction peaks of synthesized

perovskites, denote that their grain size is near micrometer and the density of intergranular defects is reasonably low. These two properties, found in deposited perovskites, make low non-radiative recombination rate possible². That is because one of the main problems that increases non-radiative recombination of charge carriers is existence of intrinsic intergranular defects. Two kinds of these defects, neutral Schottky defects and Frenkel defects are studied by DFT methods¹². Schottky defects, which are related to PbI_2 and CH_3NH_3I vacancies, do not make defect states with energies within the perovskite bandgap. Therefore schottky defects are unlikely to be effective on non-radiative recombination. However, Frenkel defects, which are elemental defects such as Pb, I and CH_3NH_3 vacancies, form shallow levels near band edges acting as non-radiative recombination centers. Diverse range of approaches for synthesis of perovskite, deposition methods and wide variety of cell structures have the main goal of reducing these defects in order to have less recombination of charges and higher currents.

Low rate of non-radiative charge carrier recombination is observed in thin layers of perovskites, in comparison with other thin-film polycrystalline semiconductors. This significant property leads to relatively small difference between open circuit voltage (V_{oc}) of cells and their effective bandgap potential (about 450meV for best perovskite cells) (E_g/q) or alternatively causes high external radiative efficiency (about 0.058%). This High external radiative efficiency makes perovskites appropriate for tandem structure of cells, bringing high value of open circuit voltage and therefore increased efficiency for the whole cell¹³. Such high maximum voltage, generated under illumination, is one of the most noticeable features of perovskite photovoltaic cells.

From other outstanding properties of perovskites, we can refer to their dielectric constant. Hybrid perovskites exhibit spontaneous electric polarization¹⁵. This lattice polarization that is affected by the polar organic cation, can be tuned through choice this cationic part of perovskite. The dielectric constant of perovskites is usually much higher than that of conventional semiconductors. This high value of the dielectric constant results from a combination of dipolar, ionic and electronic contributions. Having high dielectric constant at low excitation frequencies, makes measurement of steady-state properties possible. It is not yet determined exactly how these amounts of dielectric constants of perovskites effects photovoltaic properties¹⁴. However, it is shown that combination of high dielectric constant and low effective mass, promotes both Wannier-Mott exciton separation and effective ionization of donor and acceptor defects¹⁵.

We can think of ferroelectric and paraelectric properties of perovskites that are found at room temperature and above. The presence of ferroelectric domains will result in internal junctions that may aid separation of photoexcited electron and hole pairs, and reduction of recombination through segregation of charge carriers and therefore enhancement of photovoltaic performance. However, these properties and photoferric effects might influence performance of fabricated solar cells by manifestation in resistivity measurements and open-circuit voltage causing current-voltage hysteresis curves. Best cell performances have shown minimum hysteresis effect¹⁵.

Reviewing special properties of perovskite structures, made us enthusiastic to go through the history of cell fabrication out of them and seek the reasons for some notable achievements which made an evolution in the world of photovoltaic systems.

Historical evolution of perovskite solar cells and notable achievements

Mentioned photovoltaic features of organic-inorganic halide perovskites, have made them appropriate candidates for fabrication of different kinds solar cells. In dye-sensitized solar cells (DSSCs), perovskite plays role as a light absorber (like dyes). So there is no need for perovskite to be a good carrier transporter, because in this kind of cells, after the excitation of electrons in dye, the redox-active electrolyte or the Hole conducting medium reduces the oxidized dye back to its neutral state by electron transfer to perovskite. Therefore in these cells, it is mostly the interfacial properties which become dominant for verification of cell performance.

In fabricated sensitized cells, with nanoporous titania layer as a conventional substrate that has similar electron affinity as perovskite, the potentiality of perovskites for self-organization on this layer is observed. In 2006, solar cells with bromide halide perovskite ($CH_3NH_3PbBr_3$) and iodide/triiodide redox couple as liquid electrolyte, had efficiency of 2.2% which increased to 3.8% by substituting Bromine with Iodine. This improvement in performance of fabricated cells by this substitution of halides, originates from different incident photon-to-electron conversion efficiency (IPCE) spectra for perovskite structures with Bromine and Iodine (Figure 3)¹⁶.

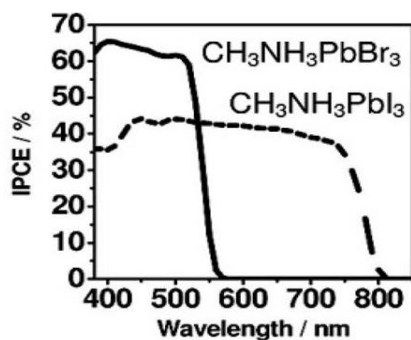


Figure 3. IPCE spectra for perovskite-sensitized solar cells¹⁶

Comparison of perovskite-sensitized solar cells with conventional DSSCs has shown much better performance of cells with perovskite. The main advantage of perovskites over conventional dyes for sensitized solar cells, is their stronger absorption over much broader range of wavelengths which is possible for layers of perovskites as thin as 500 nm. Perovskites exhibited absorption even better than standard N719 dyes. The similar fabricated cell with N719 has demonstrated solar-to-electrical conversion efficiency of 3.4%¹⁷. Further comparisons denote faster charge extraction in the first group. This observation might be because of perovskite effect on surface states or it could be the result of long-range electron transport through perovskite phase. However, as the perovskite layer deposited on mesoporous titania is not continuous, the second hypothesis about high charge extraction rate is not applicable for such perovskite-sensitized cells¹³.

The quantum dot-sensitized solar cell configuration is analogous to DSSCs. Trials to manipulate the size and shape of the perovskite nanoparticles and also modification of its substrate improved the performance of these cells. In the latest work on in 2011, hemispherical perovskite quantum dots ($CH_3NH_3PbI_3$), approximately 2.5 nm in diameter, on nanocrystalline titania substrate were used (Figure 4). Quantum dot-sensitized solar cell has an effective architecture which utilizes quantum dots as absorbers using high surface area of metal oxide supports. By applying TiO_2 surface treatment prior to deposition and electrochemical junction with iodide/iodine based redox electrolyte, perovskite QD-sensitized TiO_2 film showed maximum energy conversion efficiency of 6.54% and maximum external quantum efficiency (EQE) of 78.6% at 530nm¹⁷. The reasons for synthesis of quantum dot of perovskite are its size tunable

absorption, high extinction coefficients and multiple exciton generation. Numerous quantum dot materials had been tested for their photovoltaic performance in QD-sensitized solar cells, but their conversion efficiencies did not reach more than 1% at standard 1 sun illumination. This was until CdS QD-sensitized cells, got efficiency of more than 1% and metal chalcogenide QDs broke the record for efficiency at 4-5%¹⁷. However, metal chalcogenides as excellent inorganic sensitizers had recombination and chemical instability. Afterward, halide perovskite quantum dots were introduced which have almost overcome the problems of previous cells with considerable breakthrough in energy conversion efficiency.

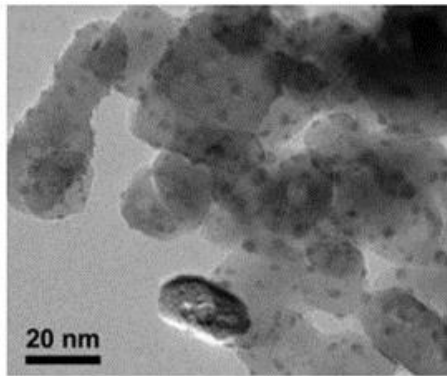


Figure 4. Wide view of $(\text{CH}_3\text{NH}_3)\text{PbI}_3$ quantum dots, deposited on porous TiO_2 ¹⁷

However, application of perovskite in liquid electrolytic solar cell has the problem of dissolution of perovskite in electrolyte that has resulted in rapid degradation of its performance, so all fabricated devices have instability problem¹⁶. This issue is somehow solved in solid-state solar cells, with hole transporting medium like Spiro-MeOTAD. Penetration of the medium solution into nanoporous titania substrate makes appropriate contact of this medium with other layers. The solution of the medium penetrates into nonporous substrates and gets solid after evaporation of its solvent. In solid-state perovskite cells, Spiro-MeOTAD is one of the best solid-state mediums.

Nevertheless, investigations have shown that PTAA (poly-triarylamine) has better performance than Spiro-MeOTAD as hole transporting medium (HTM)². Changing hole and electron transporting media (HTM and ETM), well-adjusted with energy levels of other layers in cell structure, has considerable effect on the performance of the cells. In order to achieve the highest fill factors (FFs), employing a hole transporter which has higher mobility may be necessary¹³. Application of these charge transport mediums and appropriate p-type or n-type charge collector layers, instead of liquid electrolytes, not only boosted the stability of the cells, but also enhanced the fill factors and reported efficiency to 9.7%¹⁸. This result at the very beginning of fabrication of solid-state perovskite solar cells, represented much higher potentiality of these cells than conventional ssDSSCs which had efficiencies about 7% at the highest level¹⁹.

The broad light absorption of very thin layer of perovskite is very ideal for solid-state solar cells with thickness limitations around 2 micrometer²⁰. Especially, it is observed that in extremely thin semiconductor absorber cells (ETA), the thin absorber layer, enables complete light absorption and may push the photoactivity further into the near-infrared (NIR). That is one of the reasons that hybrid organic-inorganic solid-state cells based on methylammonium lead halide perovskite absorbers (most widely used hybrid perovskite) has performed as the best thin-film photovoltaic device. It is worthwhile to mention that in ETA cells the local electric fields related to HTM and ETMs merge with each other and create a uniform field across the device. However, in cells with thick layers of perovskites these high-field regions are independent from each other²¹.

Changing the cell structures further, resulted in the boosted efficiency to 10.9%. This

good performance was obtained from cells in which the nanoporous titania was replaced with similar non-conducting mesoporous Al_2O_3 network. This insulating scaffold of Al_2O_3 acts as a buffer layer which minimizes short circuits and its porous structure is appropriate for perovskite crystallization or film formation¹³. Mentioned efficiency enhancement is mainly because of increase in the open-circuit voltage. In these cells, the charge transport occurred faster and the photocurrent remained the same that demonstrate no role of titania in photocurrent generation, but its responsibility for significant voltage loss is obvious. The difference between bandgap of the absorber and open-circuit voltage is so low that made this structure very promising for reaching high efficiencies²².

Investigations on the photoinduced charge transfer process at the surface of the perovskite were done using time-resolved techniques. Transient laser spectroscopy and microwave photoconductivity measurements were done on cells with TiO_2 and Al_2O_3 mesoporous layers covered with $CH_3NH_3PbI_3$ perovskite and Spiro-MeOTAD as the organic hole-transporting material²³. The capping layer of perovskite must have been conformally deposited on mesoporous oxide film, as optical signals are largely influenced by the presence of this layer. Alignment of conduction-band and valence-band between absorbers and TiO_2 are of crucial importance in understanding charge transfer and charge transport. Measurements have demonstrated that primary charge separation simultaneously occurs at both junctions of perovskite with mesoporous scaffold and with the HTM. And ultrafast injection of electrons and holes takes place from photoexcited perovskite over similar timescales. However, it is shown that charge recombination is significantly slower on TiO_2 than on Al_2O_3

films, indicating that the mechanism involves recombination of charges separated by a longer distance. But it is not established yet what exactly the role of mesoporous titanium dioxide is in efficient perovskite solar cell. That is because evidences claim injection of excited electrons from mixed-halide perovskite to titania substrate, while efficient photovoltaic conversion is also observed in cells when titania is replaced by insulating alumina scaffold to which electron injection from perovskite is not energetically possible (Figure 5.a). In the case of alumina, without any HTM, the only possible way for energy conservation after excitation of electron, is electron-hole recombination. Pursuing the path of charge carriers in the structure of these solar cells, which are completely in opposite directions, related to specific nature of the perovskite contact with the p- and n-type materials, we can conclude that perovskites are able to transport both electrons and holes between cell terminals, exhibiting both n-type and p-type behavior and therefore they have broader potentiality than just being a sensitizing dye⁴. Also results out of heterojunction solar cells with perovskite, introduce these semiconductors as sufficiently appropriate ambipolar charge transporters.

Schematic illustration of energy levels of the typical perovskite cell structure is shown in figure 5.b. Undesired reactions such as exciton annihilation, leading to photoluminescence (3) or to non-radiative recombination (4) and also recombination of the charge carriers at the three interfaces (5, 6 and 7), compete with the extraction of the photogenerated charges. Kinetics of all these processes, take control of overall conversion efficiency of the system²³. High power conversion efficiency of the photovoltaic device, denotes that recombination processes (3 to 7) occur much slower than charge separation and collection processes (1

and 2). In structure of these cells, for electron-hole coupling, two extremes are considered. For low-coupling extreme, it is expected for generation of free electron-hole pairs to be dominant, because exciton generation will occur mostly at wavelengths near band edges of perovskite and these generated excitons will dissociate at an interface to contribute to the photocurrent. However, in high-coupling extreme, there is an equilibration between free electron-hole and exciton concentrations²⁴.

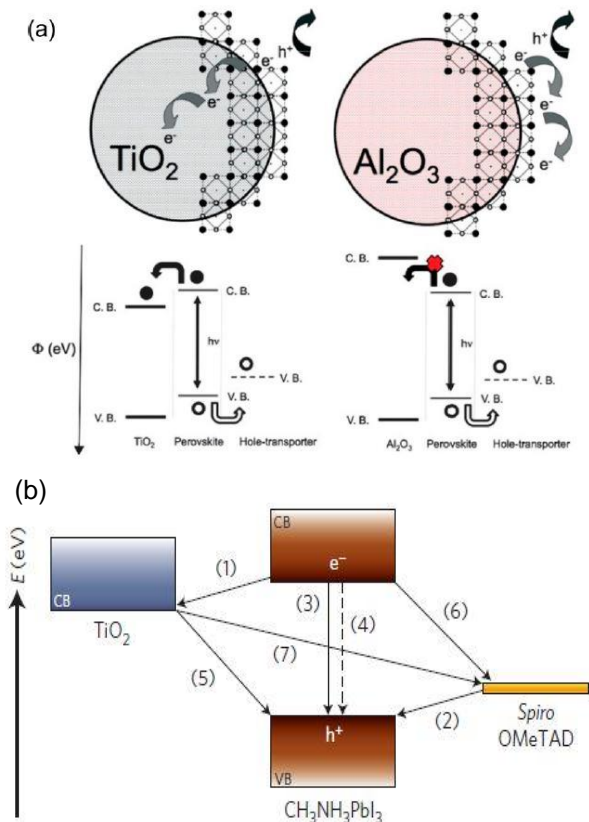


Figure 5. (a) Charge transport in deposited perovskite on titania and aluminum oxide. (b) Schematic diagram of energy levels and electron transfer processes in an HTM|perovskite|TiO₂ cell²⁴.

Some additional developments were done in perovskite structures. It is observed that synthesis and use of mixed-halides perovskite like $CH_3NH_3PbI_{3-x}Cl_x$ have exhibited better stability and charge carrier transport than pure iodide or bromide perovskites. In the mixed halide ones, the diffusion length of charge

carriers is about ten times higher than that in the pure iodine perovskites²⁵. Similar structure of mixed-halide perovskites of bromide ($CH_3NH_3PbI_{3-x}Br_x$) reached the efficiency of 12.3%. In these compounds the content of Br plays a crucial role in properties of the structure; the best initial efficiency achieved with a low Br content (<10%) due to a lower bandgap, but high-humidity stability was provided by higher Br contents (>20%)². The charge carrier diffusion length should be considered relative to the thickness of the layer. In samples made out of iodide halide perovskite prepared by the thermal evaporations, appreciable charge carrier collection were done in 350-nm-thick iodide films, denoting that the diffusion lengths exceed this thickness²⁶.

Much higher efficiencies of 15% for these photovoltaic structures, achieved by morphology improvement of titania (TiO₂) scaffolding and two-step iodine deposition²⁷. A simpler planar solar cell was constructed by mixed halide perovskite of iodine and chlorine ($CH_3NH_3PbI_{3-x}Cl_x$) (Figure 6). In this structure the deposition of perovskite was done by thermal evaporation, involving PbI_2 deposition and its conversion to perovskite by a vapour-phase CH_3NH_3I reaction, giving a better morphology and a reported efficiency of 15.4%²⁶. This result has shown that perovskite absorbers can function at the highest efficiencies in simplified device architectures, without the need for complex nanostructures.

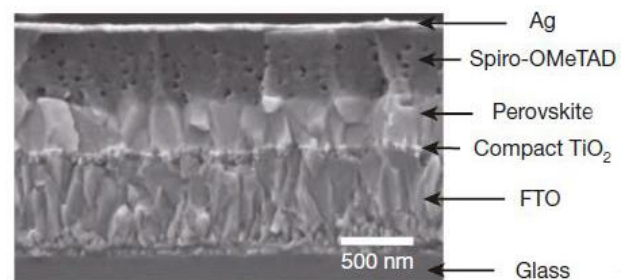


Figure 6. Cross-sectional SEM image of 15.4% efficient cell with vapor-deposited perovskite film²⁶.

At the end of 2013, cells with $CH_3NH_3PbI_{3-x}Br_x$ (10-15% Br) and the idea of using 2 optional layers of perovskite overlying the scaffold (titania), with PTAA instead of Spiro-MeOTAD, acting as the solid charge carrier mediator, were fabricated. In these cells, one layer of perovskite infiltrates the nanoporous titania substrate and the other one is as a continuous perovskite layer, resulted in high efficiency of 16.2%. In such cells in which a continuous layer of perovskite or an insulating scaffold is applied, the transport of photogenerated charge carriers across the perovskite layer becomes important, as recombination of generated carriers happen if sample thickness exceeds the optimal size. Therefore, optimization of the thicknesses of these two optional perovskite layers relative to each other, was the main key in order to improve the performance of these cells up to 17.9% in the early 2014²⁸. In the following fabricated photovoltaic devices the new hole and electron transporting mediums were applied. Analogous to the structure of standard fluorine-doped tin oxide (FTO) and titania, is indium tin oxide (ITO) as transparent conducting oxide combined with a thin ZnO-nanoparticle layer that have shown efficiency enhancement of planar cells on glass²⁹. Afterwards, even higher efficiencies up to around 20%³⁰ were reported for optimized photovoltaic systems with mixed halide perovskites and different hole transporting mediums.

One strategy for improvement of cell performance is to fabricate multi-junction cells. In single-junction cells, photons with energy more than bandgap get absorbed but as the photoexcited electrons relax back to the conduction band, that excess energy gets wasted as heat. However, in multi-junction cells, high energy photons are absorbed in wider bandgap, letting lower energy photons to get absorbed in

narrow-bandgap. So, the multi-junction cells will have higher overall voltage and less energy loss as heat. Perovskites are particularly interesting for high bandgap energy cells in tandem stacks. In these cells with effective current matching of front and rear cells, overall efficiency increases by about 1.3 times that of single junctions. So, much considerable performance, even greater than 25% efficiency is expected from tandem structures that uses both perovskite and existing technologies¹³.

One of the other strategies to further increase the efficiency of these cells is to tune bandgap of perovskites which is possible by different cation or anion choices. It has been shown that the optical spectra of the lead halide organic-inorganic perovskites can be easily changed which also tunes the emission wavelength. Narrower band-gap perovskite which absorbs out toward 940 nm, raises the efficiency by further few percent¹³.

As an overview, perovskites were initially employed as a light sensitizer in mesoporous dye cells, also function as an absorber and transport layer in solid-state dye cell architecture, and most recently as the bulk material in a standard planar thin-film solar cell. All mentioned solid-state perovskite solar cells, are categorized in three different configurations of mesoporous, planar heterojunction and meso-planar hybrid perovskite cells (Figure 7). It seems that there are two directions that are followed by these cells. One way is toward porous layers of perovskites, infiltrates with charge transporters, and another direction is to reach solid thin-film perovskite cells, most likely in the form of p-i-n heterojunction. We are looking forward for additional concepts to emerge with this family of photoactive materials.

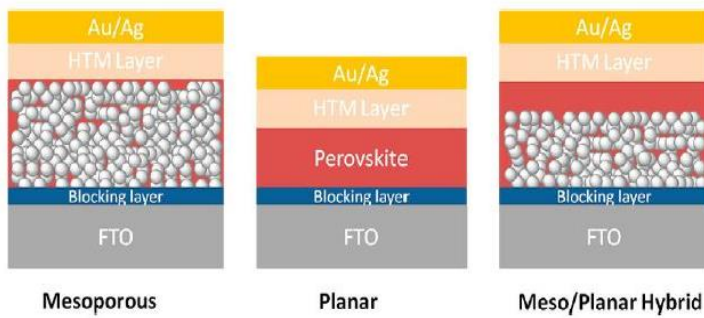


Figure 7. Schematic illustration of mesoporous, planar heterojunction and meso-planar hybrid perovskite film architecture in solar cells.

Commercialization Challenges and future prospects

Although performance of the mentioned photovoltaic devices has been very promising for reaching the goal of high energy conversion efficiency, some issues have been considerable obstacles in the way toward industrialization of perovskite solar cells. Low processing costs and high efficiencies of these cells, especially in tandem configuration, have been market advantages of perovskites. However, its reliance on environmentally hazardous heavy metal like Pb as its key component has impeded its adoption in consumer applications. Lead, as the major constituent in perovskite structure, has made it toxic. But this toxicity is not the main prevention for commercialization, since CdTe solar cells have got a very reasonable market share so far.

Precise determination of the present perovskites' features has been encouraging for identification and investigation of non-toxic materials with similar properties. Among them, Tin can be a good candidate as substitution for lead in the structure of perovskite. Tin forms similar compounds as Lead, with more ideal bandgap but with less stability against oxidation³¹.

Furthermore, perovskites are very sensitive to moisture and ultra-violet exposure.

Rapid degradation of perovskites under these conditions must be addressed by especial protective encapsulations or devising particular cell design. Perovskites apparently are stable in condition of prolonged exposure to sunlight when sealed in an inert atmosphere. The encapsulant layers restricting water vapor ingress or moisture barriers like Al_2O_3 are required in order to block humidity and preventing perovskite degradations. Although synthesis of perovskite and fabrication of the photovoltaic cells based on them have been easy and low-cost, such lack of robustness makes expensive encapsulation processes necessary for fabrication of UV-stable and air-stable cells³².

One of the key challenges for the broader photovoltaic community, has been developing wide-bandgap top cell in tandem stack with silicon or thin-film technologies¹³. Perovskites have shown their compatibility with such structures, so might overcome this challenge of tandem photovoltaic systems if their stability problem is solved.

In conclusion, hybrid perovskites offer several benefits in addition to the basic optoelectronic properties essential for an efficient photovoltaic device, i.e. spectrally suitable band-gap, high optical absorption and low carrier effective masses. In particular the ease of synthesis, tailoring of the optical absorption by chemical substitution, electronic transport, and high stability in dry air are the most prominent properties of these structures. It seems that over next few years, research and development of organic-inorganic halide perovskite solar cells will be excitingly preceded. Investigations on remaining ambiguities regarding material properties will continue and optimal cell designs and the most appropriate fabrication techniques for efficiency and performance improvements will be taken growingly under full consideration. All these

attempts are promising for commercialization of perovskite photovoltaic products in coming years in order to reach the “golden triangle” for solar technology which is cost, efficiency, and stability.

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