

Perovskite Solar Cell: a new era in Photovoltaic industry

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Abstract

Organometal-halide perovskite solar cells have recently received significant attention due to their excellent photovoltaic performance and low cost. Photovoltaic Conversion efficiency have also increased day by day and maximum reported efficiency is 20%. In this paper, different features of perovskite solar cell have been discussed including absorption coefficient and band gap engineering. Dynamic electrical model have also been discussed for the hysteresis effects in J-V characteristics of perovskite solar cells. Some critical issues have also addressed about the stability of the perovskite solar cells.

Keywords:

Photovoltaics
Perovskite solar cell
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1. Introduction

Now a day, the role and significance of renewable energy is becoming increasingly important due to the fact that main source of energy (i.e. oil, coal, uranium, etc) are limited and consequence of their use to natural balance on our planet are becoming increasingly apparent. The sun provides us daily with a tremendous and huge amount of energy which is in the form of heat and also the radiations known as solar energy. The solar energy can be used by harvesting the sunlight in the form of solar energy by using the photovoltaic device called solar cell.

Over the past four decades silicon solar cells have advanced tremendously both in terms of cost of production and efficiency [1, 2]. In some locations of the world they are delivering on grid power at competitive costs compared to that of fossil fuels. However Metal halide perovskites are the subject of intensive research efforts due to the impressive performance achieved in photovoltaic and optoelectronic devices. [3,4] The attraction toward these materials, hereafter simply perovskites, arises for a multitude of reasons. First, they show optimal primary optoelectronic properties, such as direct band gaps, long carrier diffusion lengths, and low exciton binding

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energies, resulting in the remarkable power conversion efficiency, over 22%, that these materials already deliver in optimized photovoltaic devices. These properties are accompanied by ease of processing via solution or vapor phase (or a combination of the two) techniques, low cost and abundance of base materials, low temperature of processing leading to versatility in terms of what substrates can be used, and the ability to process multiple layers on top of each other. In this review, I present the current state of the art for photovoltaic devices based on perovskites, spelling out the underlying phenomenon, different device architectures, fabrication techniques, comparison to other technologies, and future outlook and challenges. This paper is aimed at recollecting the recent developments in perovskite solar cells, providing a broader context to the reviews already published on this topic [5-8].

2. Perovskite structure and properties

Perovskites are a family of materials with the crystal structure of calcium titanate. It has a general ABX_3 ($X =$ oxygen, carbon, nitrogen, or halogen) formula, where A and B cations coordinate with 12 and 6 X anions, forming cuboctahedral and octahedral geometry, respectively. The A cation is larger than the B cation and is bulky when it occupies the cuboctahedral site (Figure 1). Although most materials with a perovskite structure are oxides, halide perovskites will be the focus of this review. In the case of the halide perovskite structure, ABX_3 (where X is F, Cl, Br, or I), monovalent and divalent cations are usually stabilized in the A and B sites, respectively. Halide perovskite structures have been known to exhibit a number of interesting optical, electrical, and magnetic properties. Perovskite formation can be estimated simply using the Goldschmidt tolerance factor (t), [9] $t = (r_A + r_X) / [2(1/2)(r_B + r_X)]$, where r_A , r_B , and r_X are the effective ionic radii for the ions in the A, B, and X sites, respectively. It has been generally accepted that perovskites can be stabilized when t is in a range between 0.76 and 1.13. [10] However, it has also been argued that perovskite structures are not stable, even in the most favorable range of $0.8 < t < 0.9$, [11] indicating that perovskite stability cannot be predicted solely based on a tolerance factor. An additional consideration for perovskite formability is the octahedral factor (μ), $\mu = r_B / r_X$. In the case of the alkali metal halide perovskite, formability was determined from the t - μ mapping, where the perovskite was stabilized for tolerance factor ranging between 0.813 and 1.107 and an octahedral factor ranging from 0.442 and 0.895 [12]

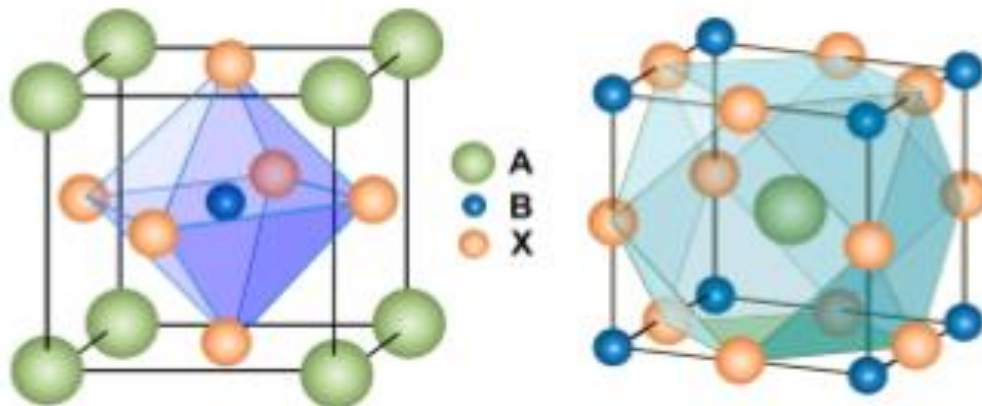


Figure 1. Typical Perovskite structure

For perovskite photovoltaic applications, A is a larger organic cation typically methyl ammonium ($CH_3NH_3^+$) with $r_A = 0.18\text{nm}$ [12], though good results have also been reported for ethyl ammonium ($CH_3CH_2NH_3^+$) ($r_A = 0.23\text{nm}$) and for mamidinium ($NH_2CH=NH_2^+$) (r_A is estimated in the range 0.19 – 0.22nm) [13].

These organic – inorganic perovskite materials possess some enticing ability and potential to be used in numerous applications because of its some amazing properties which are as follows:

i) They possess very excellent characteristics of harvesting light and also serve as very capable hole transporting medium as it has the properties of transporting the hole generated [14].

ii) They have potentially low cost for processing.

iii) These kind of solar cells are a promising option when the processing is done at a low temperature by using the printing techniques. The printing technique also make its deposition possible when they are deposited on a flexible substrate [15].

iv) Due to its high absorption coefficient, the amount of light absorbed by the solar cell is also increased which ultimately increases the amount of charge carriers generated due to the light incident i.e. photogeneration rate is increased. Due to this the loss in energy is also reduced and also the collection of charge carriers is increased at the respective electrodes [16].

v) Because of low cost of processing and the high efficiency, these devices take less time to return back the equivalent amount of energy which it has used or which is expended on the manufacturing of such devices. It is called the energy payback time which is low for this kind of material owing to its less cost involved in production and also the higher performance [17].

3. Absorption Coefficient for Perovskite Material

The value of absorption coefficient for $\text{CH}_3\text{NH}_3\text{PbI}_3$ has been reported by using a nano crystalline tin oxide film whose surface is coated by the perovskite $\text{CH}_3\text{NH}_3\text{PbI}_3$. The Figure 2 below shows the absorption coefficient plotted as a function of the various values of the wavelength for the tin oxide film coated in a nano dot fashion with $\text{CH}_3\text{NH}_3\text{PbI}_3$. The absorption coefficient has been estimated to be around $1.5 \times 10^4 \text{cm}^{-1}$ at 550 nm which indicates that the depth of penetration is $0.66 \mu\text{m}$ for light of about 550nm. At 700nm the value for the absorption coefficient was found out to be $0.5 \times 10^4 \text{cm}^{-1}$ which corresponds to a penetration depth of $2 \mu\text{m}$ which makes it suitable to be used as sensitizer for the highly efficient solid state sensitized devices of solar cells [18].

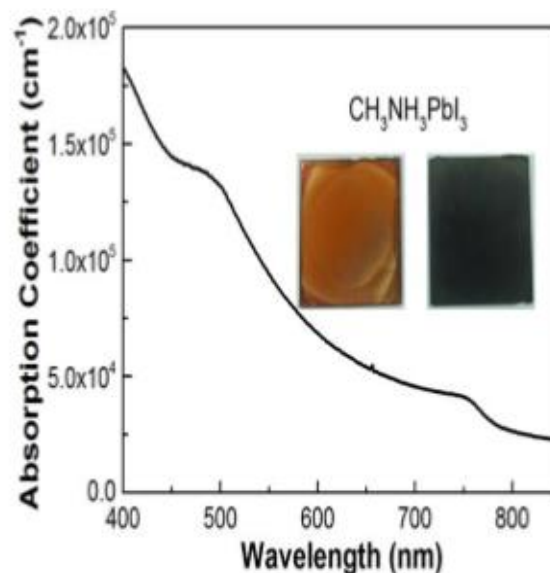


Figure 2. Absorption coefficient as a function of wavelength

Researchers [19] developed optimal design for high performance solar cell based on Perovskite material. The efficiency of solar cells without hole transport medium increases with the increase in thickness of absorber layer. With the thickness of 800 nm of the absorber layer, the value of efficiency for solar cell saturates. But due to the presence of HTM layer, the device structure can be optimized and an increase in efficiency is possible only with an absorber thickness of just 150nm. CuSCN and ZnO are used as hole transport and electron transport layers and the donor density of ZnO is less than the acceptor density of CuSCN.

Chandu V.V.M. et al [20] prepared CNT's thin films for fabricating HTM free solar cells using Perovskite and using FTO/glass as substrates. It has been suggested that the efficiency of CNTs can be increased by doping the CNT. With doping the conductivity increases. Processing CNT electrodes on top of perovskite possesses vast possibilities to be chosen so as to optimize the device materials and structure.

Mixed-halide Perovskites are reported to exhibit excellent light absorbing capabilities.[21] The substitution of the halide with the another is possible because of the lattice compatibility between different pure halides based compounds. The annealing effect also affects the opto electric properties. The band structure of the perovskite and the adjacent charge transport materials should have matching compatibility so as to enable efficient transportation of charge across the layers.

4. Band gap engineering in Perovskite material

Metal halide perovskites (ABX_3 , where A is typically Cs, methylammonium (MA), or formamidinium (FA), B is Pb or Sn, and X is I, Br, or Cl) have high power conversion efficiencies (PCEs) and low processing costs. Single junction perovskite devices have reached a certified 22% PCE [22], but the first commercial iterations of perovskite PVs will likely be as an “add-on” to silicon (Si) PV. In a tandem configuration, a perovskite with a band gap of ~ 1.75 eV can enhance the efficiency of the silicon cell.[23] An all-perovskite tandem cell could deliver lower fabrication costs, but requires band gaps that have not yet been realized. The highest efficiency tandem devices would require a rear cell with a band gap of 0.9 to 1.2 eV and a front cell with a band gap of 1.7 to 1.9 eV. Although materials such as $FA_{0.83}Cs_{0.17}Pb(I_xBr_{1-x})_3$ deliver appropriate band gaps for the front cell [23], Pb-based materials cannot be tuned to below 1.48 eV for the rear cell. Completely replacing Pb with Sn can shift the band gap to ~ 1.3 eV (for $MA\text{SnI}_3$)(3), but the tin-based materials are notoriously air-sensitive and difficult to process, and PV devices based on them have been limited to $\sim 6\%$ PCE.[24, 25] An anomalous band gap bowing in mixed tin-lead perovskite systems ($MAPb_{0.5}Sn_{0.5}I_3$) has given band gaps of ~ 1.2 eV but mediocre performance ($\sim 7\%$ PCE). Very recently, PCE of over 14% has been reported with $MA_{0.5}FA_{0.5}Pb_{0.75}Sn_{0.25}I_3$ cells, for band gaps > 1.3 eV and all perovskite 4 terminal tandem cells with 19% efficiency.[26-28]. Here, we demonstrate a stable 14.8 % efficient perovskite solar cell based on a 1.2 eV bandgap $FA_{0.75}Cs_{0.25}Pb_{0.5}Sn_{0.5}I_3$ absorber. Open-circuit voltages (VOCs) of up to 0.83 V in these cells, which represents a smaller voltage deficit between band gap and VOC than measured for the highest efficiency lead based perovskite cells. We then combined these with 1.8 eV $FA_{0.83}Cs_{0.17}Pb(I_{0.5}Br_{0.5})_3$ perovskite cells, to demonstrate current matched and efficient (17.0 %) monolithic all perovskite 2-terminal tandem solar cells on small areas and 13.8 % on large areas, with Voc > 1.65 V. Finally, 20.3 % efficient small area and 16.0 % efficient 1cm² all-perovskite four-terminal tandems using a semitransparent 1.6eV $FA_{0.83}Cs_{0.17}Pb(I_{0.83}Br_{0.17})_3$ front cell have been fabricated

Figure 3(a) shows Scanning electron microscope (SEM) images of the top surface of $FASn_xPb_{1-x}I_3$ films with different Sn percentages and $FA_{0.75}Cs_{0.25}Pb_{0.5}Sn_{0.5}I_3$, fabricated with the PAI deposition technique. The 0% Sn films were annealed at 170 °C, while the other films were heated at 70 °C. Fig 3(b) provides the plot of experimentally estimated bandgap as a function of Sn %, determined from absorption onset in a Tauc plot of the absorption and PL peak positions. In this case the bandgap is assumed to be direct. Bandgaps for Sn-Pb perovskite alloys calculated from first principles using a supercell containing eight BX_6 octahedra, where the Sn and Pb atoms are ordered relative to each other.

5. Dynamic characteristics of Perovskite material

Dynamic electrical model of the solar cell is shown in figure 4. The basic elements are: the current source, a diode with ideality factor n, the shunt and series resistances and the capacitance, which is here introduced by a polarization mechanism. This model is utilised by researchers to study the dynamic J-V characteristics.

The hysteresis of the dynamic J-V characteristic is also known for other types of solar cells, but only when the voltage sweep is fast [29], whereas in perovskite cells it is obtained at sweep rates of Volt per minute. The origin of this anomalous hysteresis is still under debate and has been attributed to different phenomena, such as a giant photo -induced dielectric response [30], ferroelectric effects [31, 32], ion migration [33] possibly accompanied by charge trapping and detrapping [34], or unbalanced distributions of electrons and holes [35, 36].

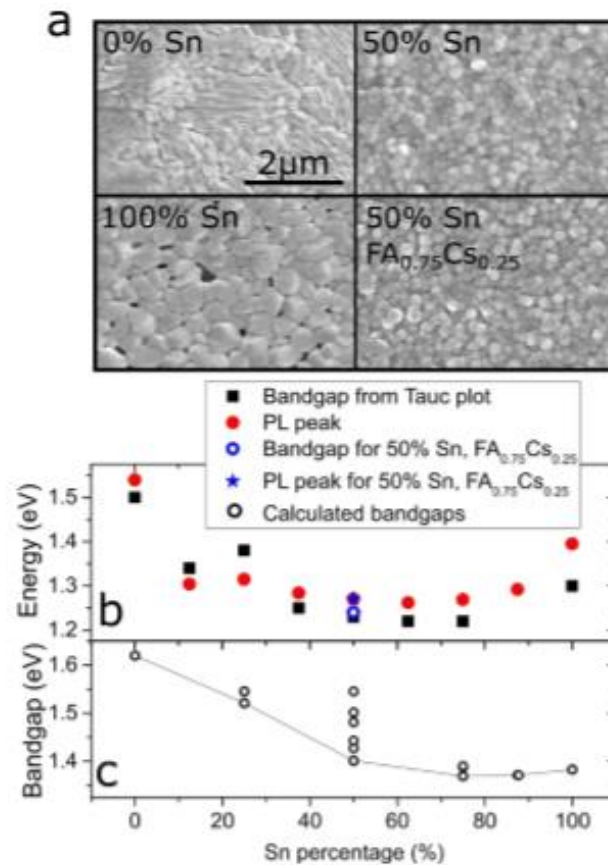


Figure 3. (a) SEM image of the top surface of $\text{FaSn}_x\text{Pb}_{1-x}\text{I}_3$, (b) Band gap as a function of Sn%, Band Gap for Sn-Pb perovskite alloys calculated from first principle using a super cell containing eight BX_3 octahedra

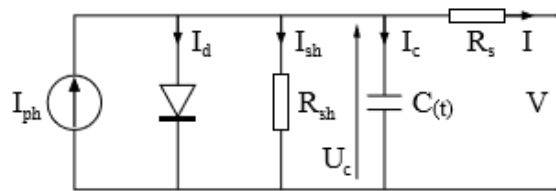


Figure 4. Dynamic electrical model of Solar cell

It is a well known fact that variations between the J-V characteristics under forward and reverse bias scans arise in the presence of a large capacitance, for a high BSR. In forward scan, a fraction of the photo-generated current charges the built-in capacitor, leading to smaller values in the current than in reverse scan, when the capacitor releases the charges, leading to relatively larger PCEs. In perovskite solar cells a slow decay of the photovoltage was observed and initially related to capacitive effects introduced by a giant photoinduced dielectric constant [27]. Ferroelectricity is another potential cause considered for the observed hysteresis. Yet it is a controversial hypothesis, as the time-scales involved are typically below ms [38], which lends the idea of microscopic

ferroelectricity [39]. It is important to note, however, that capacitive effects alone cannot reproduce different pre-conditioning effects induced by initial light soaking and pre-poling by different biases [40].

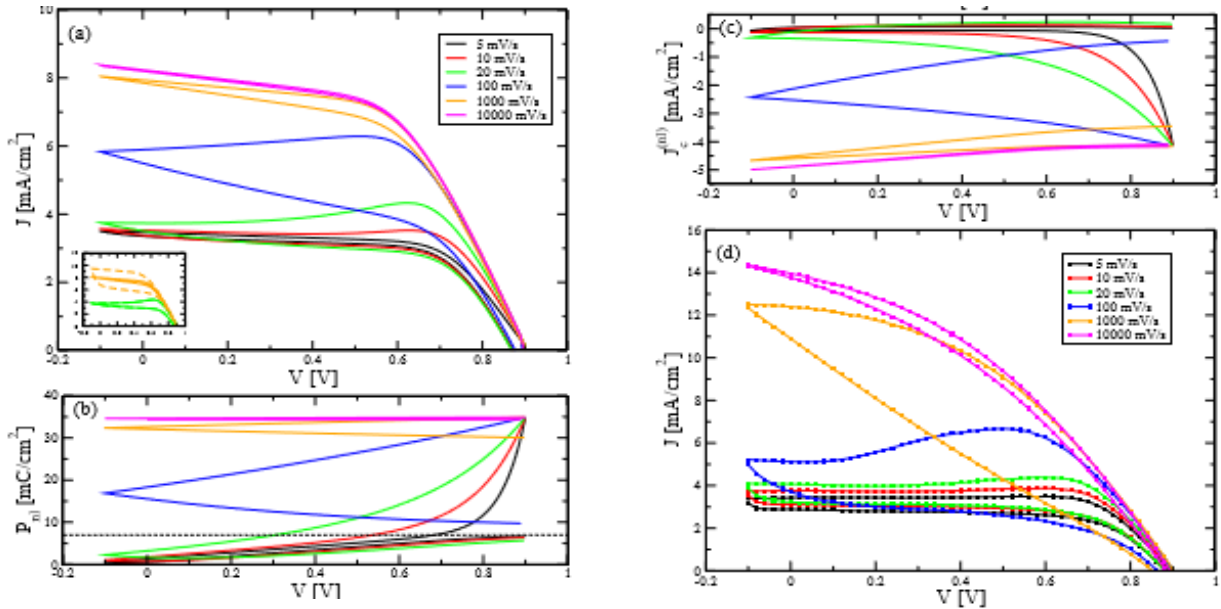


Figure 5. Dynamic hysteresis under different bias scan rates: (a) simulated J-V characteristics [30], the inset shows simulated J-V characteristics for a large value of dielectric constant= 10^5 (dashed line) [37], (b) the corresponding polarization, (c) the current component J_c^{nl} , (d) experimental JV characteristics at different BSRs

As was later found, the capacitive effects are quite independent on the thickness of the perovskite layer, which suggests that the induced polarization is related to interfacial properties, including ion accumulations near the electrodes. Trapping and de-trapping processes near the interfaces and grain boundaries are also thought to play a role in the hysteretic behavior [34]. More recently the ionic migration mechanism is gaining ground. The perovskite being known as a ionic conductor, Tress et al. [41] argued for a non-electronic reason for the hysteresis, based on several observations, such as: relaxation time scales between seconds to minutes, strong dependence on BSR and temperature, or counter balancing of the polarization for applied voltages of relatively high negative values. A recently proposed drift-diffusion model taking into account ionic migration however shows that the observed hysteretic behavior may be obtained only by including electronic charge traps, serving as recombination centers [42].

6. Major Challenges Faced by Perovskite Solar Cells

Kai Tan et al reported that PCE of solid-state perovskite solar cells has achieved 20.1% recently [43], which is quite comparable with silicon and CIGS solar cells in photovoltaic field. Although the perovskite solar cell materials have numerous advantages but these materials too face many challenges.

i) The perovskites employed for manufacturing solar cells are very sensitive oxygen and water vapours. The presence of oxygen and water vapors degrade these PV cells very quickly. This problem This method is not very effective for large scale This can increase the life span of a solar cell for a time period of four months [44].

ii) One of the most commonly used material in perovskite based solar cells is lead, which is toxic in nature. Lead can leach out from the panel of solar cell panel into the surroundings into the environment and can cause various

ecological and health related challenges. For this very problem an environmentally friendly and benign element like tin has been into the proposition as an alternate source to lead based perovskites [45].

iii) Perovskite based solar cells are reported to possess lower lifetime because of phase transition. Few studies on storage lifetime suggested their operation under sealed conditions at 45°C. Under such conditions the observers the initial Power Conversion Efficiency was found to be 20% after 500h [46].

7. Conclusions

Metal-halide perovskites are significant for research and commercialization of solar cells in the next few years due to its high efficiency. Absorption coefficient is very high in visible wavelength range. Drastic change in band gap can be obtained by changing Tin percentage in perovskite composition. A dynamic electrical model has been discussed to describe hysteresis effects observed in halide perovskite based solar cells. Much of the work in case of perovskite materials has been done using lead Halides combination. Relatively few work is reported in the field of Tin based perovskite films. Owing to the low cost, better stability and easy fabrication process, the perovskite solar cells will be able to contest with the traditional silicon based photovoltaic devices in near future.

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