The King of the New Generation Photovoltaic Technologies—
—Perovskite Solar Cells & the Opportunities and Challenges

Qianyu Chen
The School of Automobile and Traffic Engineering, Wuhan University of Technology, Wuhan, Hubei 430070, People’s Republic of China
Chenqianyu121112@163.com

Abstract. Within the past several decades, photovoltaic technology is an emerging pioneer in the renewable energy field. Driven by the rapid decline in the price of photovoltaic products, the cost of photovoltaic power generation is becoming cheaper or even lower than the cost of thermal power generation. Among various photovoltaic technologies, organic-inorganic hybrid perovskite thin film solar cells are promising candidates for the next generation of solar cells in consideration of their outstanding advantages such as low-cost, easy manufacturing processing and high power conversion efficiencies. Perovskite solar cells stem from dye-sensitized solar cells. Within less than a decade of rigorous research and development in perovskite solar cells, the efficiency is boosted up to 25.2%. Aforementioned high PCE is mainly attributed to outstanding photovoltaic properties such as the long diffusion length of carriers, high optical absorption coefficient, excellent carrier mobility, etc. Meanwhile, the main barriers of commercialization for the perovskite solar cells are the poor stability of the devices, and the possible environmental pollution caused by lead. Herein, we briefly reviewed the opportunities and the challenges of this game changer in photovoltaic field. The development prospective are also discussed.

Key words: perovskite, solar cells, photovoltaic materials,

1. Introduction
With the gradual decrease of total amount of non-renewable fossil resources such as oil, coal and natural gas, the development and utilization of renewable and environmentally friendly new energy has become a major issue in the world. In the field of photovoltaics, Si-based photovoltaic devices have been making a great contribution, but their cost does not show an obvious advantage compared to the conventional energy. Compared to Si-based photovoltaic devices, perovskite solar cells can be fabricated at lower costs. Meanwhile, the power conversion efficiency (PCE) of perovskite solar cells has evolved from 3.8% [1] to 25.2% [2] which demonstrated a promising future in the related field. (Figure 1) In the past years, solar devices based on perovskite materials have been a superstar in the research institutes, and the number of publications and citations of related scientific and technological papers demonstrate a fierce growth trend. Since 2013, the number of papers published on perovskite solar cells has been growing continuously, and now it is about 3-4 thousand a year. Herein we mainly discuss the advantages and disadvantages of perovskite solar cell and the future prospect of it.
2. The opportunities of perovskite solar cells

Featuring extreme low cost and skyrocketing efficiency, organic-inorganic hybrid halide perovskite solar cells have emerged as the most promising superstar in PV technology field. There are several unique advantages of perovskite solar cells like the low fabrication expenses and mild device processing. To prepare the traditional silicon wafers, high vacuum and hot processing above 1000 °C are inevitable in several steps, whereas perovskite solar cells only need some mild chemistry processing in the commonly available ambient environment.

2.1 The organic-inorganic hybrid structure of perovskite materials

Perovskite solar cells have shown excellent photovoltaic properties in just a few years. Take other kinds of solar cells as references, studies indicate that the high efficiency of perovskite solar cells is mainly due to their organic-inorganic hybrid structure[3]. Such an organic-inorganic hybrid structure has several merits in some crucial properties of the materials, which is showed in the following passage.

2.1.1 Bandgap tuning of perovskite materials. Perovskites for photovoltaics have an intriguing characteristic that their band gap can be tuned by simple compositional substitution. Nevertheless, ordinary halide substitution cannot offer a way to reduce the band gap below 1.48 eV. There are two strategies to achieve lower band gap:

I. A site replacement in ABX₃ perovskite[4] This method can be combined with the B-site doping method. To conduct a further research on the influence of the A cation size in the perovskite materials, GE Eperon et al replaced the MA constituent with Cs and FA. The experimental results demonstrated that 1.48 eV could be obtained, allowing larger spectral absorption. It is further demonstrated that as the A cation increasing in ionic radius, the lattice would be expected to be larger and the bandgap would be reduced, leading to a red-shift in the absorption onset. Beyond MA and FA, organic cation guanidinium (CH₆N³⁺ GA) with a size of around 278 pm[5], which is larger than the size of FA⁺(≈253 pm)[5]

II. Directly mutating the M-X bond. In spite of replacing the A site or B site cation, modifying the M-X bond can also tune perovskite band gap. According to the theoretical study, the band edges are adjudged by the orbitals of B-cation metals, therefore, the energy band structure will be affected. Likewise, band-gap running can be achieved by varying the halide of M-X bond. Jun Hong Noh et al
fabricated inorganic-organic heterojunction solar cells with an entire range of MAPb(I\(_x\)Br\(_{1-x}\)). When the x was changed from 0 to 1, the band gaps were changing between 1.5 and 2.3 eV[1][6]. It was worthy of mention here that this kind of cells performed steadily when the x equals 0.2.

2.1.2 High carrier mobility of perovskite materials. Carrier mobility equals the ratio of the carrier moving velocity and the intensity of the applied electric field. Jongchul Lim et al [7] found that there were obvious differences in the remote carrier mobility of the composite films of perovskite fabricated by various preparation processes, such as solution based spin-coating and vacuum vapor deposition, in the range from 2.2 to 0.2 cm\(^2\)V\(^{-1}\)s\(^{-1}\). Compared to the polycrystalline perovskite films, perovskite single crystals showed better transport properties (\(\approx 60\) cm\(^2\)V\(^{-1}\)s\(^{-1}\)) and smaller trap densities (\(\approx 10^{10}\) cm\(^{-3}\)) [8][9]

All through the compositional range, FA\(_{0.85}\)MA\(_{0.15}\)PbI\(_3\) and FA\(_{0.15}\)MA\(_{0.85}\)PbI\(_3\) single crystals performed the optimum carrier mobility. Therefore, Huang et al [10] obtained mobility based on the Mott-Gurney law. They estimated the hole mobility and the electron mobility of FA\(_{0.85}\)MA\(_{0.15}\)PbI\(_3\) perovskite single crystals, which is 5.31 cm\(^2\)V\(^{-1}\)s\(^{-1}\) and 10.19 cm\(^2\)V\(^{-1}\)s\(^{-1}\) while the two data for FA\(_{0.15}\)MA\(_{0.85}\)PbI\(_3\) perovskite single crystals are 0.60 cm\(^2\)V\(^{-1}\)s\(^{-1}\) and 0.77 cm\(^2\)V\(^{-1}\)s\(^{-1}\), respectively. Above mentioned data indicates that the carrier mobility of FA\(_{0.85}\)MA\(_{0.15}\)PbI\(_3\) is higher than FA\(_{0.15}\)MA\(_{0.85}\)PbI\(_3\), which illustrates the high dependency of mobility and the organic cation ratio in the composition.

2.1.3 High optical absorption coefficient of perovskite materials. Absorption coefficient is one of the most important standards to evaluate the quality of an optical material. A high absorption coefficient usually means that only a very thin layer of optical material can absorb enough light, which can decrease the performance loss derived from the undesired charge recombination. In detail, MAPbI\(_3\) has the absorption coefficient of larger than 3.0\times10^4 cm\(^{-1}\) in the visible region, which is over 10 times larger than that of silicon, indicating that the thickness of the absorption layer of perovskite is much smaller than that of crystalline silicon. In addition, numerous reports have pointed out that the thickness of organic and inorganic perovskite batteries is about 0.3-0.6μm, while the thickness of crystalline silicon solar cells is about 300μm. In that case, the fabrication investment of perovskite solar devices should be smaller than the conventional silicon solar wafers.[12][13]

2.1.4 Longer diffusion length of carriers. Samuel D. Strank et al reported the carrier diffusion lengths of MAPbI\(_3\) and MAPbI\(_3\):Cl\(_x\). Both of them had over 1 micron diffusion length which further led to the high efficiency of perovskite solar device.[14] These experimental outputs can form important foundation for the research of perovskite solar cells.

2.2 Cost advantages of perovskite solar cells
In comparison with other kinds of photovoltaic technology, cost is an important advantage of perovskites. Song et al [15] developed a bottom-up cost model to evaluate the cost of perovskite solar cells modules fabricated with low-cost materials and processes. The manufacturing process which used a large area, low temperature deposition technique step by step was shown in the flowing diagram (Figure 2). The fabrication cost was estimated to be $5.5–31.7/m\(^2\) which was consisted of the perovskite cells process ($1.2–6.8/m\(^2\)) and the related balance of module components ($4.3–24.9) such as glass, frame and etc.
Figure 2. The manufacturing flow chart of perovskite solar cells modules. [15].

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Cai et al[16] estimated the fabrication cost and showed a cost analysis of two representative kinds of perovskite modules. One of them was average efficient modules with mesoporous structure mainly based on cheap materials and the screen printing solution (module A), the other was highly efficient solar devices with accurate structure and high cost materials (module B), the whole calculated cost of materials for module A was 0.127 $/W while the cost for module B was 0.102 $/W.[17]

Later, Chang et al also analyzed the LCOE of a single-junction module. Compared to the LCOE of CdTe modules and water based c-Si modules respectively are $86$/m$^2$ and $136$/m$^2$. They mainly researched the LCOE of three kinds of perovskite solar cell modules. Sequence A relies on gold evaporation for metallization, while sequence B substitute gold for silver, and sequence C is special for the removal of the sacrificial metal mask process for patterning the c-TiO$_2$ layer. The LCOE of these mentioned sequence are $175$/m$^2$, $102$/m$^2$, $90$/m$^2$, respectively. [18]

Nonetheless, different researchers adopt different ways to estimate the manufacturing cost of perovskite solar cells, all these results support the great potential of solar cells based on perovskite devices. The cost of different types of the PSCs is relatively lower than the traditional energy resources. The Table 1 shows the four different research results about the cost of the perovskite solar cells.

Table 1. The information comparison of several perovskite solar cells modules from different researchers.[15][16][18][19]

| Reference | Module assumption | Estimated cost | Device structure | Key layer function method |
|-----------|-------------------|----------------|-----------------|--------------------------|
| From [15] | PCE: 16%          | 3.5–4.9 US cents/kWh | Front glass/ITO/NiO/CH$_3$NH$_3$PbI$_3$/ZnO/Al/Frame/junction-box | ITO and Al: industrial-scale magnetron sputtering, The charge transport layers(NiO and ZnO): screen printing followed by a post-deposition heat treatment,PbI$_2$: single-step screen printing, Perovskite layer: deposit by MAI mixture dissolved in a dimethylformamide (DMF) and dimethyl sulfoxide (DMSO) solution |
| Lifetime: 30 years | | | | |
| | | | | |
| From [16] | Assumed PCE:12% | 4.9 US cents/kWh | Glass/TCO/Mesoporous scaffold perovskite layer/back | TiO$_2$: Spray pyrolysis Scaffold layers: multiple screen printing Perovskite material: dip-coated within the mesoporous scaffold by moderate thermal annealing |
| Module A Based on a mesoporous structure | Assumed PCE:15% | 4.2 US cents/kWh | electrode/encapsulation layer | |
| | | 3.5 US cents/kWh | | |
3. The challenges of perovskite solar cells

Although the perovskite solar cells have made an incredible progress in high efficiency and showed great advantages in the manufacturing cost, many barriers still remain on the way to perovskites’ commercialization, among which the stability issue of the perovskite materials is a big trouble for the researchers especially under the influence of some external conditions such as oxygen, water, and ultraviolet light. In addition, the toxicity of lead is also a challenge to be overcome when considering the future feasible application.

3.1 Stability improvement of perovskite solar cells

The factors which can have impact on the stability of perovskite solar cells are listed as follows: the intrinsic chemical stability of perovskite solar cells, the stability of the solar energy device, the influence of external natural conditions. In addition, impacted by the electric field, the perovskite materials are not only easy to polarize. Finally, when the perovskite absorption layer and other functional layers are combined, the issue of instability is more serious. In terms of these issues, researchers mainly optimize the stability in the following two strategies. One is improving the intrinsic chemical stability of perovskite crystals, the other is avoiding the direct contact of perovskite absorber with those above-mentioned adverse factors. Here we mainly introduce four methods to alleviate these problems.

3.1.1 Additive engineering. Ionic liquid additives have previously been incorporated in the precursor in order to improve the long-term operational stability of the perovskite solar cells. Recently Bai et al employed a simple, widely used method, they added ionic liquids 1-butyl-3-methylimidazolium tetrafluoroborate(BMIMBF_4) to the (FA$_{0.83}$MA$_{0.17}$)$_{0.95}$Cs$_{0.05}$Pb(I$_{0.8}$Br$_{0.2}$)$_3$ of the perovskite precursor. According to the experimental results, it was demonstrated that 0.3%mol doing could get the optimized result with a PCE of 19.8% under a light intensity of 105mW/m$^2$. Furthermore, the device could retain 85% of the initial efficiency after aging for 1885 hours[20]. Wang et al novelly proposed the trivalent and divalent europium ion pair that could alternatively oxidize Pb and reduce I defects at the same time. The modified solar cell could obtain a PCE of 21.52% with a certified efficiency of 20.52% with largely improved long-term durability. The devices could retain 92% and 89% of the champion PCE after continuous illumination or 1500 hours of heating at 85°C and 91% of the initial PCE after aging for 500 hours under maximum power point conditions.[21]

3.1.2 Compositional engineering of perovskite materials. Compositional engineering is another effective method to enhance the stability of devices based on perovskite materials. In this aspect, Zhou et al incorporated the CsI into the inorganic skeleton based on the precursor chemistry, which could greatly modify the film nucleation dynamics during the film formation. The results indicated that not
only the efficiency of $\text{FA}_{0.9}\text{Cs}_{0.1}\text{PbI}_{3.4}\text{Cl}_{x}$ based device but also the stability were greatly improved[22]. Furthermore, the total replacement of fragile organic species with stable inorganic cations would lead to all-inorganic perovskite devices. Lyubov A. Frolova et al systematically investigated the all-inorganic perovskite material $\text{C}_{x}\text{S}_{3}\text{PbI}_{2}\text{Br}_{x}$, where $x$ had a value range from 0.95 to 4. When the $x$ equalled 1.2, the $\text{C}_{81.2}\text{PbI}_{1.2}\text{Br}_{1.2}$-based device had the best structural, device performance (the PCE is over 10%), as well as the optimized stability, in comparison with $\text{CsPbI}_{3}\text{Br}$, which could generate $\text{CsPbBr}_{3}$ and $\text{CsPbI}_{3}$ via a disproportionation reaction under the stress of ultraviolet irradiation or high temperature[23].

### 3.1.3 Interface modification of perovskite solar cells

Interfaces play an important role in the functioning of perovskite voltaic devices. Therefore, it is essential to pay enough attention to the design and optimize interfaces between each functional layer to optimize the device stability. Yang et al fabricated the $\text{PbSO}_{3}$ and $\text{PbI}_{4}(\text{PO}_{4})_{3}$ passivation layers by a simple chemical reaction of perovskite with $\text{SO}_{4}^{2-}$ or $\text{PO}_{4}^{3-}$ salts, after which a thin and dense inorganic lead-oxygen layer was generated on the top interface of perovskite. In comparison with the intermolecular forces, the strong chemical bond between perovskite and passivation materials could enhance the resistance ability towards light and moisture. Apart from that, it could also enhance the carrier lifetime and improve the efficiency of solar cells up to 21.1%. After aging for 1200 hours at 65 °C under maximum power point tracking, the modified device could retain 96.8% of the initial efficiency.[24] Besides, Bu et al demonstrated that using the phenylethylammonium iodide could reduce the iodide vacancy as well as the generation of superoxide. Experiment results showed that solar devices assembled with it could obtained better stability as well as enhanced the device PCE at the same time.[25].

### 3.1.4 Encapsulation technology for perovskite solar cells

Last but not least, encapsulation technology is also an effective method to improve the stability perovskite solar cells and protect them from environmental factors including moisture, oxygen and light. Ashraf Uddin et al summarized a series of different materials and technologies for encapsulation, and listed various situations where different packaging materials are appropriate. Until now, people have developed different interface layers as barriers to protect perovskite layers but they are not sufficient. By contrast, encapsulating the devices with glass is the most efficient and effective method so far, which may be vastly applied in the perovskite device during its industrial manufacturing. In addition, many other materials such as Ethylene methyl acrylate, Ethylene vinyl acetate, Polyvinyl butyral, Thermoplastic polyurethane and etc., may be effective methods for device encapsulation as well.[26].

### 3.2 Possible environmental pollution caused by lead

Apart from the stability issue of solar cells based on perovskite materials, the impact on the environment is also one big challenge for the vast application of perovskite solar cells. For instance, when the perovskite solar modules are used outdoors, they may be corroded by natural factors such as rainfall, high winds, and fires, which can lead to the release of toxic lead from the damaged modules, which could further cause damage to natural environment. In that case, there are mainly two effective methods to reduce the lead pollution, encapsulation technology and doping method, namely partial replacement of toxic lead with Sn. What’s more, Douglas Fabini et al had tried to quantify the possible upper limit of lead contamination during the lifetime of the perovskite solar cells modules. Based on the simulation result, it took 38 μg of lead to generate one kWh of electricity based on perovskite solar cells under the assumption that the lifetime and the efficiency are 25 years and 25% respectively.[27].
3.2.1 Encapsulation technology. As mentioned in the previous context, encapsulation can make a positive contribution to preventing lead leakage. Jiang et al investigated three packaging methods for perovskite solar devices under the simulation situations and recorded the amount of lead leakage under various weather simulations. The result showed that epoxy encapsulation could reduce lead leak rate by 375 times in comparison with glass encapsulation, which was mainly attributed to epoxy coating’s self-healing performance and strong mechanical strength.[28]

3.2.2 Doping method. Partial replacement of lead with nontoxic tin is another effective strategy to reduce the possible pollution of perovskite solar devices. In this aspect, Hao et al did a pioneer work and adopted the tin-based materials (CH$_3$NH$_3$SnI$_3$) to fabricate perovskite solar cells. Compared with 1.5 eV bandgap of the conventional MAPbI$_3$, the tin-based one was only 1.3 eV, which showed better performance for sunlight harvesting. Besides, other properties like the mobility of carriers were better than the traditional one.[29] Further, Efat Jokar et al developed a Sn-based perovskite solar cells with the crystal structure of FASnI$_3$ doped different proportions of GA’ When the ratio of FAI to GAI in the precursor was 8 to 2, the obtained solar cell demonstrated a initial PCE of 8.5%, after being stored in a glove box for two thousands hours, the efficiency continued to be improved to 9.6%.[30]

4. Conclusion
As one of the most efficient ways to use solar energy, solar cells have attracted worldwide attention. However, many kinds of solar cells cannot provide satisfactory device performance in consideration of those key factors such as cost, efficiency and stability. The organic and inorganic hybrid perovskite solar cells have rapidly rose to prominence within a few years and set off another research upsurge in the field of photovoltaics with good performance and a wide range of development prospects. The efficiency of perovskite solar cells has been up to 25.2% and it is still developing rapidly under the joint efforts of researchers. Herein we briefly reviewed the opportunities and challenges of the perovskite solar cells. The advantages mainly include the high efficiency in the solar performance, simple film preparation process, impressive physical properties and low fabrication cost, nevertheless, the disadvantages cover the poor stability, short lifetime and the toxicity of raw material etc.

5. Envisioned Future
Back in 2013, the perovskite solar cell was awarded as one of the ten scientific breakthroughs of the year by science journal. It is even being expected to realize its commercialization in the following decades and become a new generation of mainstream solar cells beyond monocrystalline silicon cells. It is worthy to mention here that there is still space to further reduce the module costs of perovskites solar cells such as the replacement of expensive electrode materials and the optimization of the film formation method in the large area device production. Even so, lots of obstacles to the large scale commercialization still remain and numerous technological challenges need to be overcome urgently. We believe that in the near future, perovskite-based clean and sustainable energy will occupy the mainstream of photovoltaic field, and perovskite solar cells will make great contributes to the human society.

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