

Research Progress and Optimization Strategy of Trans-calcite Solar Cells

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Abstract: Against the background of clean energy attracting much attention, the development of chalcogenide solar cells is rapid, and the reverse chalcogenide cell is one of the research hotspots. This paper systematically introduces the structure, working principle, preparation method of chalcogenide thin film, and optimization strategy of each part of the inverse chalcogenide solar cell. The structure of the chalcogenide solar cell contains a transparent conductive oxide layer, a hole transport layer, a chalcogenide light absorption layer, an electron transport layer and a metal electrode. During operation, sunlight excitation generates electron-hole pairs, which are transported to form an electric current. The preparation methods mainly include one-step solution deposition method and two-step solution deposition method. In terms of optimization, the chalcogenide light-absorbing layer is optimized by means of interfacial modification and control of precursors; the electron-transporting layer is improved by mixing fullerenes and designing fullerene derivatives; and the performance of the hole-transporting layer is enhanced by using novel materials and adjusting energy levels. These studies provide a reference for the further development of trans-calcitonite solar cells.

Keywords: chalcogenide solar cell, energy level, interface modification

1. Introduction

With the development of science and technology, the problem of energy shortage has become a key issue constraining the sustainable development of society. Currently, with the introduction of policies such as carbon peak carbon neutral, clean energy is therefore attracting much attention. Solar energy, as a renewable and clean energy source, is gradually becoming a powerful alternative to traditional fossil fuel energy. Chalcogenide solar cells have made remarkable development breakthroughs in the past decade, showing great commercial potential with their high stability and excellent photovoltaic conversion performance. Previous research on chalcogenide solar cells has mainly centered on mesoporous chalcogenide cells and planar chalcogenide cells, and planar chalcogenide cells can be subdivided into formal and trans structures, with trans chalcogenide dominating the current research.

In the study of trans-calixarene solar cells, Peter Chen et al. proposed that strategies such as using PEDOT: PSS as a hole transporting layer were used to prepare trans-calixarene solar cells [1], and high photoelectric conversion efficiencies were already achieved at that time, which fully proved the good application of the trans-calixarene solar cell Effect.

However, despite the progress made, there are still some pending issues in the research of trans-CaTi solar cells. Currently, there is no literature to systematically sort out and summarize the research

progress on the evolution of its working principle, the development of electron transport layer and hole transport layer, the preparation and synthesis methods, and the defect treatment. Based on this, this paper will focus on the development dynamics of trans-calcium titania solar cells in recent years, systematically introduce the above key components, and propose corresponding optimization and improvement strategies for each part, with a view to providing references for further research in this field.

2. Principle of trans-calcite solar cells

2.1. Structure of calcitonite solar cells

A typical trans-type chalcogenide solar cell is shown in Fig. 1, from bottom to top: transparent conductive oxide layer (Transparent Conductive Oxide), hole transport layer (hole transport layer), chalcogenide light-absorbing layer (Perovskite), electron transport layer, metal electrode (Metal).

(1) Transparent Conductive Oxide Layer: This layer is the sunlight incident surface and serves as the anode of the battery. Generally used indium tin oxide (ITO) or reference tin oxide (FTO) as raw materials.

(2) Hole transport layer: acts as a channel for hole transport and prevents electron transport at the same time. Materials such as nickel oxide [2] or cuprous compounds [3] can be used as the hole transport layer, but nowadays Sprio-OMeTAD is more commonly used as the hole transport layer in trans-Calcium-Titanium-mineral solar cells.

(3) Chalcogenide light absorption layer: Chalcogenide is an ionic crystal with the chemical formula ABX_3 and has a crystal structure as shown in Fig. 2, with A standing for $CH_3NH_3^+$, $CH(NH_2)_2^+$ or Cs^+ , and B standing for Pb^{2+} or Sn^{2+} , and X is generally a halogen ion, such as I^- , Br^- or Cl^- .

(4) Electron Transport Layer: It serves as a channel for electron transport and prevents the transport of holes at the same time. Generally, n-type semiconductors such as TiO_2 , SnO_2 , and ZnO are used as electron transport layers. Now more often used is TiO_2 as the electron transport layer. TiO_2 layer consists of dense TiO_2 and mesoporous TiO_2 two layers of material, which, dense TiO_2 is used to prevent the conductive base and chalcogenide direct contact, to avoid the transmission of holes to the conductive substrate; mesoporous TiO_2 for the growth of chalcogenide to provide a support for the formation of a hybrid layer for the transmission of electrons.

(5) Metallic electrodes: Metallic electrodes generally use common conductive materials such as gold, silver, and copper as the cathode of a Calcium-Titanium solar cell.

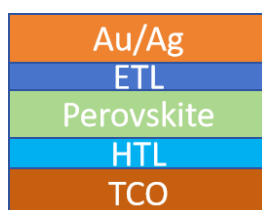


Figure 1: Structure of trans-calcitonite

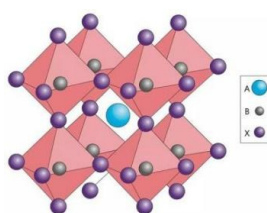


Figure 2: Structure of chalcogenide

2.2. Principle of operation of trans-calcitonite solar cells

When the sunlight irradiation to the transparent conductive oxide layer, the photons in the energy higher than the width of the forbidden band of chalcogenide will be absorbed by the chalcogenide, excitation of chalcogenide in the valence band of the electrons. Electrons from the valence band away from the conduction band to reach the point of the valence band in the formation of holes, so that the electron-hole pairs are called excitons. Under the action of heat energy, the exciton changes into free electron and free hole. At this time the Fermi energy level of chalcogenide changes from unity to split electron Fermi energy level E_{fn} and hole Fermi energy level E_{fp} , The directional movement of the electrons and the holes occurs, and each of them moves from chalcogenide layer to the hole. They each flow from the chalcogenide layer to their own transport layer, and finally to the electrode, which turns on the external circuit circuit, forming a loop and generating an electric current [4,5].

2.3. Preparation of chalcogenide thin films

There are various methods for the preparation of chalcogenide thin films, such as one-step solution deposition, two-step solution deposition, anti-solvent method, and solution-vapor phase deposition.

The one-step solution deposition method dominates the field of chalcogenide thin film preparation and is widely used. The one-step solution deposition method involves mixing metal halides and organic ammonium salts in organic solvents in a certain ratio to form a precursor, and then the precursor is uniformly coated on the substrate by spin-coating, and then finally, after a series of operations such as deposition, annealing, and so on, a chalcogenide film is obtained. Going back to the origin of this method, Miyasaka et al. [6] carried out research work. They successfully constructed a TiO_2 mesoporous layer by using FTO as a substrate material, coating TiO_2 nanocrystals on the surface of the substrate, followed by sintering treatment at a specific temperature and environment. Subsequently, PbX_2 and $\text{CH}_3\text{NH}_3\text{X}$ were thoroughly mixed according to the calculated stoichiometric ratios and allowed to dissolve in γ -butyrolactone solvent to form a homogeneous precursor solution. With the aid of spin-coating technique, the above precursor solution was uniformly spin-coated on top of the TiO_2 mesoporous layer at a constant speed and time. After a series of physicochemical processes, the finally obtained $\text{CH}_3\text{NH}_3\text{PbX}_3$ showed a typical chalcogenide crystal structure. Under the technical background at that time, the photoelectric conversion efficiency of the solar cell prepared based on this method could reach 3.8%, which laid an important foundation for the subsequent research and development of chalcogenide solar cells. Later, Guo et al. [7] pioneered the preparation of chalcogenide thin films on organic PEDOT: PSS substrates using a one-step spin-coating process. During the study, the two solvents, GBL and DMF, were compared and analyzed, and it was found that the chalcogenide films prepared by them showed obvious defects in the morphology and poor densification. The chalcogenide material itself has excellent properties, but the high boiling point solvents, such as GBL and DMF, are weak in volatility, which makes the chalcogenide film prone to agglomeration when using this simple preparation method. In order to optimize the morphology of the chalcogenide films, the researchers have innovatively proposed a series of improvement strategies based on the traditional one-step spin-coating method. For example, changing the composition and ratio of raw materials or adding additives to the precursor solution to control the crystallization process.

In recent years, the two-step solution deposition method has also attracted much attention. This method requires the pre-preparation of a metal halide film precursor, to which an organic ammonium salt is subsequently added dropwise by spin-coating. After sufficient reaction, a series of operations such as deposition and annealing are performed to obtain chalcogenide thin films. Gratzel et al. [8] prepared a metal halide layer MI_2 thin film (M is a group IVB metal) on a TiO_2 mesoporous substrate by using spin-coating deposition and then immersed the whole thin film into an organic salt solution.

The experimental results show that the solubility of organic ammonium salts in organic solvents is higher in the two-step solution deposition method compared to the one-step solution deposition method. This effectively alleviates the problem of low amount of chalcogenide deposition due to the relatively low solubility of the precursor generated by the reaction of metal halide with organic ammonium salt solution in organic solution. In 2023, Paetzold et al. [9] proposed a new idea to improve the two-step deposition method. The addition of bromide after the metal halide deposition and before the organic ammonium salt deposition allowed the chalcogenide solar cells to produce more carriers when operating, which in turn improved the operating efficiency of the cells. 2024 Du et al. [10] also improved the preparation process of the two-step solution deposition method. They added (RbCl) and VB4 (RCVB) to the metal halide (PbI₂), and utilized the two-step solution deposition method to precisely control the content of the metal halide to form structural intercalation layers and constructed chalcogenide thin films with a good energy level match. Ultimately, the open-circuit voltage was enhanced to 1.17 eV, and the photoelectric conversion efficiency (PCE) was increased to 21.68%.

3. Advances in the optimization of trans-calcium titanate cells

Optimization of the efficiency and other aspects of the chalcogenide battery has always been the goal of researchers relentlessly pursued. At present, various research groups mainly focus on the optimization of chalcogenide absorption layer, electron transport layer and hole transport layer, and constantly put forward new optimization ideas.

3.1. Development of calcite light absorbing layers

There are various methods to optimize the light-absorbing layer of chalcogenide. Interfacial modification is recognized as a widely used and proven means. In 2019, Wang et al. [11] introduced a multifunctional ammonium salt (CTAB) on the surface of chalcogenide films. Among them, the long-chain CTA⁺ cations were able to be immobilized on the film, and the Br⁻ ions were uniformly distributed on the film surface to exert the passivation effect of Br⁻ ions. Compared with the untreated devices, the devices with CTAB showed significant improvement in photoelectric conversion efficiency (PCE) and operational stability.

In addition to interfacial modification, many other methods for optimizing chalcogenide light absorbing layers have emerged in recent years. For example, the surface morphology and properties of chalcogenide light absorbing layers can be modulated by controlling the precursors. Elnaggar [12] found that adjusting the stoichiometric ratio of PbI₂ and MAI precursors can significantly improve the surface homogeneity of the chalcogenide film, and at the same time, increase the degree of crystallinity, which can lead to higher PCE. As shown in Table 1, the PCE of the cell reaches 19.6% when the ratio of PbI₂: MAI is 1.5: 1.45. Wang et al. [13] found that the surface homogeneity of chalcogenide films can be improved by adjusting the stoichiometry of PbI₂ and MAI precursors, and that the PCE of the cells is 19.6%. The PCE of the cell reaches 19.6%. Wang et al. [13] on the other hand, increased the grain size of chalcocite by changing the precursor solvent and using the antisolvent ether as the solvent in order to improve the PCE. As shown in Table 2, the PCE of the cell is 15.09% when the ratio of the ether is 4%, which is an enhancement of more than 20% in comparison with the control group.

Kong et al. [14] optimized the preparation process of chalcogenide thin films. The ion-binding additive betahistine mesylate was added during the grain nucleation and growth stages of the preparation of coated spins in order to increase the grain size, Improve the specific surface area, and thus enhance the PCE. As shown in Fig. 3, the addition of the ion-binding additive resulted in a PCE of up to 24.19% as compared to the control, and the initial efficiency of 94% could still be maintained for 2712 h at 25 °C and 50% air humidity. In addition, the initial efficiency of 94% can be maintained for 2712 hours under 25°C and 50% air humidity.

Changing the crystal type of the chalcogenide film is also one of the ways to optimize the chalcogenide light absorbing layer. For example, Chen et al. [15] adapted the cell structure to a p-i-n structure. They prepared MAPbI₃ single-crystal flakes with thicknesses roughly in the range of 10 - 40 μm on hydrophobic ITO/PTAA substrates. Subsequently, the surface passivation treatment using MAI effectively reduced the defect state density on the single crystal surface. Finally, the cell achieved an efficiency of 17.8%. This achievement is of great significance in the field of monocrystalline cells, and plays a leading role in the improvement of efficiency and rapid development of subsequent devices.

Table 1: Comparison of JV curve data for different ratios of PbI₂ vs. MAI

PbI ₂ :MAI (Molar Ration)	V _{oc} ^{ave±SD} (V _{oc} Best) [V]	J _{sc} ^{ave±SD} (J _{sc} Best) [cm ⁻²]	FF ^{ave±SD} (FF Best) [%]	PCE ^{ave±SD} (PCE Best) [%]
1.3:1.25	1.02±0.03 (1.07)	17.0±2.0 (18.8)	61.0±6.0 (67.0)	11.5±1.0 (13.5)
1.4:1.35	1.07±0.01 (1.08)	19.4±0.2 (19.2)	68.0±1.4 (71.0)	14.4±0.5 (15.1)
1.5:1.45	1.14±0.01 (1.15)	22.4±0.8 (22.6)	70.5±4.0 (75.5)	18.1±1.1 (19.6)
1.6:1.55	1.04±0.04 (1.08)	18.8±0.9 (19.5)	58.0±3.4 (64.0)	11.4±1.4 (13.5)

Table 2: Comparison of JV curve data for different ether additions

Blend ratio	V _{oc} (V)	J _{sc} (mA/cm ²)	J _{sc} (mA/cm ²)	FF(%)	PCE(%)
Device A(0%)	1.08	16.20	16.12	75.66	13.28
Device D(5%)	1.06	19.20	14.27	61.67	12.60
Device E(10%)	0.91	15.91	13.65	64.37	9.29

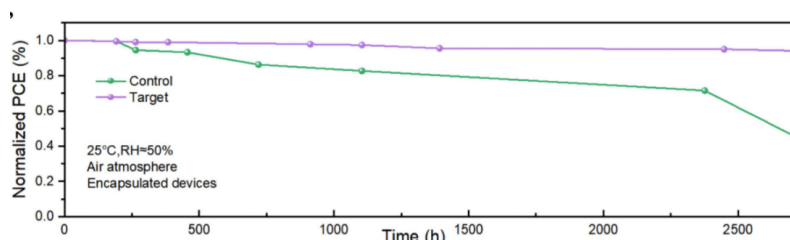


Figure 3: Comparison of batteries under long cycle

3.2. Development of chalcogenide electron transport layers

For the improvement of the efficiency of chalcogenide cells, the improvement of the electron transport layer is crucial. In trans-calcium titania cells, fullerenes and their derivatives (PCBM) are

mainly used to prepare organic electron transport layers at this stage. The main reasons for choosing them are their high electron transport capacity and good thermal stability, as well as their ability to passivate the interface and reduce the potential barriers, thus improving the efficiency of chalcogenide cells.

Dai et al. [16] optimized the properties of pristine fullerenes by employing hybrid fullerenes (C60 and C70) instead of a single fullerene as the electron transport layer. The XRD results showed that the hybrid fullerenes suppressed the crystallization phenomenon, which was conducive to the preparation of a uniform electron transport layer. The SEM images revealed that the non-uniform aggregation was unfavorable to the electron transport compared with the severe aggregation phenomenon in the control group when C60 and C70 were formed as separate films. And the aggregation problem could be effectively alleviated and the electron transport ability could be enhanced when C60 and C70 fullerenes were doped at a ratio of 1:1. By measuring the current-voltage curves and external quantum efficiency, it can be seen that the best cell performance performance can be obtained when 1:1 doped C60 and C70 with photoelectric conversion efficiency (PCE) up to 14.04% (as shown in Table 3), which is basically comparable to that of the commonly used PCBM cells (13.74%).

Moreover, in addition to changing the stoichiometric ratio of different fullerenes, it is also an idea that has attracted much attention. For example, Xing et al. [17] designed and synthesized a series of fullerene derivatives containing oligomeric ether (OE) chains as the electron transport layer for calixarene solar cells. It was found that the OE chains were able to stabilize the fullerene electrons and regulate the lowest unoccupied molecular orbital (LUMO) energy level, which was beneficial for electron extraction. At the same time, the film has a smaller contact angle and interaction with the chalcogenide surface passivates the trap state. As shown in Table 4, the PCE of the improved electron transport layer, such as C70 - DPM - OE, can be as high as 16%, which is higher than the efficiency when PCBM is used as the electron transport layer (ETL), and provides a new idea for the subsequent improvement work.

Improvement of PCBM itself is also promising. Xia et al. [18] doped amphiphilic surfactant oleamide (oleamide) in PCBM electron transport layer to optimize the electron transport layer. The electron transport layer (ETL) was prepared by adding different ratios (1 wt%, 5 wt%, and 10 wt%) of oleamide into the PCBM solution. And the results showed that the best performance of PCBM was achieved when the ratio of oleamide was 5 wt%. And the PCE efficiency could reach up to 12.69% (as shown in Table 5), whereas too much or too little doping led to a decrease in performance. Characterization of the films by SEM and AFM observed that due to the intermolecular interactions between PCBM and the hydrophobic long alkyl chains of polyamide molecules, the aggregation of PCBM molecules was inhibited during solvent evaporation, which resulted in a more ordered molecular stacking of PCBM. Improved the coverage of the PCBM electron transport layer on the calixarene layer, and facilitated the interfacial interface between the calixarene layer and Ag cathode contact as well as electron transport between the chalcogenide layer and Ag cathode.

Table 3: Comparison of JV curve data for C₆₀ and C₇₀ doped with different ratios

Weight ratio	V _{oc} (V)	J _{sc} (mA/cm ²)	FF(%)	PCE(%)
C ₆₀ only	0.946	17.78	55.39	9.32
4:1 C ₆₀ :C ₇₀	0.930	18.86	64.31	11.27
1:1C ₆₀ :C ₇₀	0.946	21.01	70.64	14.04
1:4C ₆₀ :C ₇₀	0.936	19.83	65.55	12.16
C ₇₀ only	0.943	17.43	61.93	10.18
PC ₆₁ BM	0.932	20.97	70.29	13.74

Table 4: Electron mobility of different electron transport layers

ETL	Electron Mobility ($\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$)
C ₆₀ -DPM-OE	5.0x10 ⁻⁴
PC ₆₁ BM	1.3x10 ⁻³
C ₇₀ -DPM-OE	3.3x10 ⁻⁴
PC ₇₁ BM	1x10 ⁻³

Table 5: Plot of JV curve data after addition of oleamide

ETL	V _{oc} (V)	J _{sc} (mA/cm ²)	FF (%)	PCE (%)	R _s ^b ($\Omega \cdot \text{cm}^2$)	R _{sh} ^b ($\Omega \cdot \text{cm}^2$)
PCBM	0.95	17.08	61.8	10.05	17.7	961.4
Oleamide:PCBM	0.98	18.76	69.3	12.69	4.8	940.8

3.3. Optimization of chalcogenide hole transport layer

Jie et al. [19] discovered and used the novel material Cu₂BaSnS₄ (CBTS) to regulate the thickness of the hole transport layer and optimize it. Conventional organic hole transport layer materials are susceptible to humidity and oxidation, while inorganic P-type materials have low hole mobility, which hinders the improvement of cell efficiency. Jie et al. found that CBTS is an intrinsic P-type semiconductor due to the Cu defects, and the Cu vacancies are shallow subject to the dominant energy level, which is easy to ionize, and other defects have high formation energies with good chemical stability, high carrier mobility, and can be a better hole transport layer material. Meanwhile, they also compared different thicknesses of CBTS films, and the best cell effect occurs when the CBTS film is 100 nm thick, and the PCE can reach about 10%.

Zhang et al. [20] discovered and used a series of anionic polyelectrolytes based on poly (arylidene vinylidene) to tune the energy level alignment and optimize the hole transport layer. Conventional materials for hole transport layers, such as PEDOT: PSS, although widely studied in the early stage, have some limitations, and their work function adjustment is more difficult to achieve the ideal energy level matching with the chalcogenide layer, which affects the charge extraction efficiency. And some inorganic compounds perform poorly in terms of interfacial compatibility with the chalcogenide layer when they are used as hole transporting layers. Zhang et al. found that anionic polyelectrolytes based on poly (arylidene vinyls), such as PVBT - SO₃, PVF₂BT -SO₃, and PVF₄-SO₃, are able to efficiently tune their conjugated backbone structures due to their tunable HOMO energy levels. These polymers contain the same sulfonate side groups, which ensures similar surface energies and reduces the interference of other factors on the charge extraction and transport of chalcogenides, as well as good chemical stability and solution processability. They also compared the device performance of different polymers when used as hole transport layers. The results show that the devices perform best when using PVBT - SO₃ as the hole transport layer, with a maximum photoelectric conversion efficiency (PCE) of 18.4%.

Chen et al. [21] explored sputtered crystalline MoO₃ thin films with annealing treatment, which provided a new direction for the optimization of hole transport layer in inverted chalcogenide solar cells. Traditional organic hole transport materials, like PEDOT: PSS, have outstanding problems in practical applications, being sensitive to humidity, which can seriously affect the device stability in humid environments, resulting in a significant reduction in performance. And some inorganic hole transport materials, such as NiOx, have unsatisfactory hole mobility and impeded charge transport process, which greatly limits the room for improvement of battery efficiency. Its research found that the sputtered MoO₃ films showed excellent performance by annealing treatment. During the annealing process, adjusting the temperature can change the degree of crystallization and conductivity

of the films. When the annealing temperature was controlled at 300°C, crystalline MoO₃ films were prepared with significantly improved hole transport properties compared to those in the amorphous state. This is attributed to its crystalline structure, which creates favorable conditions for carrier migration and is chemically stable in air to maintain a good working condition.

4. Conclusion and outlook

In this paper, starting from the structure of trans-calcite solar cells, the raw materials and functions of each functional layer, such as transparent conductive oxide layer, hole transport layer, chalcite light absorption layer, electron transport layer and metal electrodes, are elucidated. For the chalcogenide light-absorbing layer, the commonly used methods include (1) interfacial modification, (2) controlling the preparation of the chalcogenide layer precursor, and (3) changing the crystal structure of the conventional chalcogenide. All three methods have achieved good results, especially the change of the crystal structure of chalcogenide, which has a crucial impact on future development. For the optimization of the electron transport layer, the efficiency of the chalcogenide electron transport layer was significantly improved by using (1) hybrid fullerenes, (2) fullerene derivatives, and (3) PCBM and its improved derivatives. The hole transport layer, on the other hand, enhanced the hole transport performance and improved the cell efficiency by using novel materials, adjusting the energy level alignment, and optimizing the preparation process.

However, optimization improvements also bring new problems. Overcoming the defects created by the layers cannot be ignored. Laboratory preparation faces the challenge of large-scale production. Exploring new cell structures during optimization, such as tandem and stacked structures, can give full play to the advantages of different materials, broaden the spectral response range, and increase the upper limit of the cell photoelectric conversion efficiency. Even the combination of artificial intelligence and machine learning technology to assist the design and optimization of cell structures can accelerate the development process of new high-efficiency cells. In conclusion, the preparation and optimization of trans-CaTiO solar cells still need to be continuously explored.

References

- [1] Jeng, J.-Y., Chiang, Y.-F., Lee, M.-H., Peng, S.-R., Guo, T.-F., Chen, P. and Wen, T.-C. (2013), CH₃NH₃PbI₃ Perovskite/Fullerene Planar- Heterojunction Hybrid Solar Cells. *adv. mater.*, 25: 3727-3732.
- [2] Zhu Z, Bai Y, Zhang T, et al. High-performance hole-extraction layer of sol-gel-processed NiO nanocrystals for inverted planar perovskite solar cells [J]. *Angewandte Chemie-International Edition*, 2014, 53(46): 12571-12575.
- [3] Christians J A, Fung R C M, Kamat P V. An inorganic hole conductor for organo-lead halide perovskite solar cells. improved hole conductivity with copper iodide [J]. *Journal of the American Chemical Society*, 2014, 136(2):758-764.
- [4] Y. Wang. Preparation of highly efficient and stable trans-calcite solar cells based on interfacial modulation[D]. Hebei University,2024.
- [5] Gao, F., Zhao, Y., Zhang, X., & You, J. (2020). Recent progresses on defect passivation toward efficient perovskite solar cells. *Advanced Energy Materials*, 10(13), 1902650.
- [6] Kojima, Akihiro, et al. "Organometal halide perovskites as visible-light sensitizers for photovoltaic cells." *Journal of the american chemical society* 131.17 (2009): 6050-6051.
- [7] Wu, Po-Ting, et al. "The impact at polar solvent treatment on p-contact layers (PEDOT: PSS or NiOx) of hybrid perovskite solar cells." *Organic Electronics* 73 (2019): 273-278.
- [8] Bi, Dongqin, et al. "Using a two-step deposition technique to prepare perovskite (CH₃NH₃PbI₃) for thin film solar cells based on ZrO₂ and TiO₂ mesostructures." *Rsc Advances* 3.41 (2013): 18762-18766.
- [9] Pappenberger, Ronja, et al. "Bandgap Engineering of Two-Step Processed Perovskite Top Cells for Perovskite-Based Tandem Photovoltaics." *Advanced Functional Materials* 34.9 (2024): 2311424.
- [10] Du, Zhuowei, et al. "PbI₂ intercalation and residual elimination strategy for sequential inverted perovskite solar cells." *Chemical Engineering Journal* 503 (2025): 158587.
- [11] Wang, Shuo, et al. "Interface modification by a multifunctional ammonium salt for high performance and stable planar perovskite solar cells." *Journal of Materials Chemistry A* 7.19 (2019): 11867-11876.

- [12] Elnaggar, Mohamed M. "Optimizing PbI₂: MAI precursor ratio for enhanced surface uniformity and performance inverted perovskite solar cells." *Materials Letters* 384 (2025): 138133.
- [13] Wang, Huiping, Wenjin Zeng, and Ruidong Xia. "Antisolvent diethyl ether as additive to enhance the performance of perovskite solar cells." *Thin Solid Films* 663 (2018): 9-13.
- [14] Kong, Zhuoyuan, et al. "Dual-stage Crystallization Regulation for Efficient and Stable Perovskite Solar Cells." *Materials Today Energy* (2025). 101836.
- [15] Chen, Zhaolai, et al. "Thin single crystal perovskite solar cells to harvest below-bandgap light absorption." *nature communications* 8.1 (2017). 1890.
- [16] Dai, Si-Min, et al. "Pristine fullerenes mixed by vacuum-free solution process: efficient electron transport layer for planar perovskite solar cells." *Journal of Power Sources* 339 (2017): 27-32.
- [17] Xing, Yue, et al. "New fullerene design enables efficient passivation of surface traps in high performance pin heterojunction perovskite solar cells." *Nano Energy* 26 (2016): 7-15.
- [18] Xia, Fei, et al. "Efficiency enhancement of inverted structure perovskite solar cells via oleamide doping of PCBM electron transport layer ." *ACS applied materials & interfaces* 7.24 (2015): 13659-13665.
- [19] Ge, Jie, Corey R. Grice, and Yanfa Yan. "Cu-based quaternary chalcogenide Cu₂BaSnS₄ thin films acting as hole transport layers in inverted perovskite CH₃NH₃PbI₃ solar cells." *Journal of Materials Chemistry A* 5.6 (2017): 2920-2928.
- [20] Zhang, Zhewei, et al. "Understanding hole extraction of inverted perovskite solar cells." *ACS Applied Materials & Interfaces* 12.50 (2020). 56068-56075.
- [21] Chen, Lung-Chien, et al. "Annealing effect of sputtered crystalline M₂O₃ films on hole transporting in inverted type perovskite solar cells." *2017 Progress In Electromagnetics Research Symposium-Spring (PIERS). IEEE*, 2017.