Proceedings of the 5th International Conference on Materials Chemistry and Environmental Engineering
DOI: 10.54254/2755-2721/124/2025.20002

Low-Temperature Processed Perovskite Solar Devices with High Photoelectric Conversion Performance

Ruochen Gu[1,a,*]

[1]*BASIS Independent Mclean, Mclean, US*
a. richardguu22@gmail.com
**corresponding author*

Abstract: This study presents the development of high-performance perovskite solar cells (PSCs) processed via low-temperature methods, utilizing dimethylacetamide (DMAc) as a solvent. By comparing its performance with the standard dimethylformamide (DMF) under both high (100 °C) and low (20 °C) temperature conditions, we demonstrate that DMAc-based PSCs maintain exceptional quality even at reduced processing temperatures, a pivotal advancement for scalable and cost-effective manufacturing. Furthermore, the formation of uniform, high-quality perovskite films is readily achieved, which is crucial for efficient light harvesting and favorable charge carrier dynamics. Photoluminescence (PL) and X-ray diffraction (XRD) analyses reveal DMAc's superiority in trap state passivation, yielding fewer defects, higher crystallinity, and larger crystallite sizes than DMF. Furthermore, transient photovoltage (TPV) measurements analysis confirms extended charge carrier lifetimes in DMAc-containing PSCs, accounting for their enhanced stability and, on average, higher power conversion efficiencies (PCEs). This work underscores the potential of DMAc as a game-changing solvent for advancing perovskite solar cell technology toward high-efficiency, low-cost, and flexible devices, poised for commercialization in the photovoltaic industry.

Keywords: Perovskite, Low–temperature Fabrication, Solar Cell, Crystallinity, Low defect density.

1. Introduction

The development of perovskite photovoltaics has garnered significant attention in recent years due to their potential for high efficiency, low cost, and ease of fabrication.[1] The most common perovskite is a hybrid organic-inorganic lead halide material, for instance, methylammonium lead halide (CH3NH3PbX3). This material is solution-processable materials with a direct bandgap, large absorption coefficient, strong photoluminescence, and high charge-carrier mobility, making them efficient light-harvesting materials in solar cells, crucial for improving device efficiency and stability through their intrinsic photophysical properties.[2]

The first perovskite solar device achieved an initial power conversion efficiency (PCEs) of 4% using perovskite materials as a dye for sensitization in 2009 by Miyasaka et al.[3] Significant progress was made in 2012 when several research groups reported over 10% PCEs by employing mesoporous nanostructures.[4] This breakthrough attracted great attention in the field of photovoltaics. In 2015, perovskite solar cells showed extraordinary PCEs ranging from 12% to over 15% using a planar

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/124/2025.20002

device structure and whole solid designation.[5] This rapid improvement in efficiency has made perovskite solar cells one of the most exciting new photovoltaic technologies available today. When focusing on the electron transfer properties associated with the charge transfer layers, the PCEs skyrocketed to 20.1% after electron transfer layer (ETL) doping.[6] Until, 2024 this number has reached 25.87% in steady state, and 26.15% when optimized.[7] This progress shows the potential for perovskite solar cells to combine high efficiency with low cost and scalable processing, which could revolutionize the photovoltaic industry.

For perovskite solar cells (PSCs), the core component is the perovskite absorber layer, making up of organo-lead halide perovskite materials. Surrounding this layer are charge transport layers, such as TiO2 or mesoporous carbon, which play a crucial role in collecting and transporting photogenerated charge carriers.[8] The unique composition of perovskite materials and their efficient device structure are key to the high performance of these solar cells. In terms of structure, PSCs can be categorized into two main configurations: mesoscopic and planar. The mesoscopic nanostructure, akin to dye-sensitized solid-state solar cells, features perovskite dots adsorbed onto a TiO2 surface, facilitating charge separation through electron injection from the perovskite to the TiO2. Conversely, the planar structure eliminates the mesoporous TiO2 layer.[9] Here, the charge transport and accumulation within the perovskite layer itself are vital to the cell's functionality. This structure has been found to offer more efficient transport and recombination rates compared to the mesoscopic configuration. The planar device structure is often denoted by the p-i-n (positive-intrinsic-negative) configuration, consisting of a transparent conducting oxide (TCO), an ETL, the perovskite light absorber layer, a hole transport layer (HTL), and a metal electrode. Meanwhile, the n-i-p structure reverses the layer sequence of the p-i-n, with the TCO and HTL positions flipped.[10] Recent trends in PSCs have favored planar structures over mesoporous ones due to advantages like lower temperature processing, compatibility with organic electronics manufacturing, and the potential for flexible device applications.

In terms of performance, perovskite solar cells have achieved efficiencies exceeding 26%, which, combined with their compatibility with low-cost solution processing, positions them as a promising technology. The integration of perovskite materials with other solar technologies, like silicon, to form high-efficiency tandem cells, further underscores their potential.[11] However, challenges such as stability issues, measurement-induced hysteresis, and other factors continue to impact performance. Efforts to reduce the manufacturing costs of perovskite solar cells include adopting low-temperature techniques like printing, blade coating, and spray coating.[12] Ongoing research aims to optimize the cost-performance balance, which is crucial for realizing the commercial potential of perovskite solar cells and ensuring they are economically accessible. Moreover, perovskite solar cells have demonstrated the ability to be fabricated on various substrates, including flexible materials, expanding their potential for applications in wearable devices and other flexible electronics.[13] The low-cost nature of perovskite materials, combined with their abundant availability, makes them an attractive option for large-scale manufacturing.

The preparation process of perovskite solar cells is crucial for their efficiency and performance. Various fabrication techniques, including solution processing and vapor deposition, have been explored to optimize perovskite thin films. Solution-based methods, such as spin-coating and inkjet printing, are favored for their simplicity and low-temperature processing capabilities. These involve depositing a perovskite precursor solution and annealing at relatively low temperatures. Low-temperature processing is essential as it expands substrate and electrode material options, including flexible substrates, and reduces energy consumption and manufacturing costs. Significant progress has been made in developing low-temperature techniques that achieve efficiencies comparable to high-temperature methods.

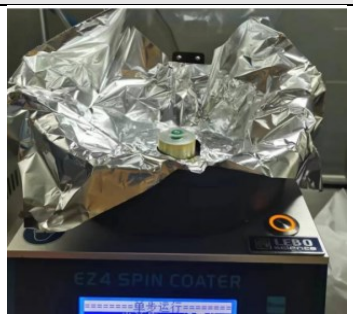
DOI: 10.54254/2755-2721/124/2025.20002

2. Experimental: Processing diagram

1. ETL Fabrication



1: Creating a solution of tin oxide (SnO2)



2: Spin-coated onto a substrate and annealed at high temperature to form a thin, uniform layer



3: Annealing the SnO2 layer

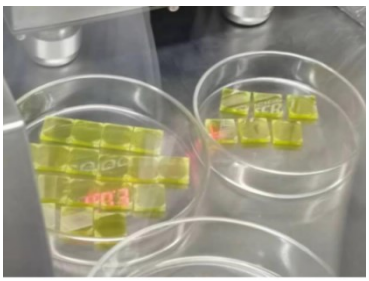
2. Active Layer Fabrication



1: Dissolving lead iodide (PbI2) and MAI in a solvent to create a precursor solution



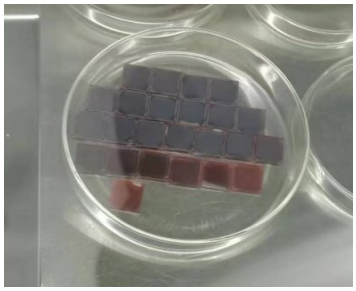
2: The precursor solution is deposited onto the ETL and initially annealed at a lower temperature to form a lead iodide film.



3: PbI2 film complete

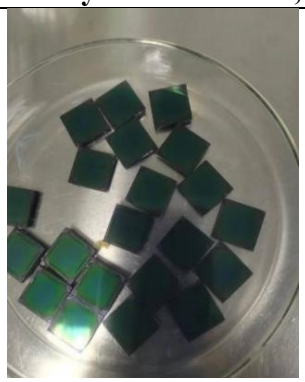


4: Continue adding the organic salt solution onto the pre-formed PbI2 film using spin-coating technique.



5: Initial Perovskite Film Formation, and annealing under 100 °C for control device. And no thermal treatment for DMAc device (20 °C).

DOI: 10.54254/2755-2721/124/2025.20002

3. HTL layer Fabrication, deposit electrode		
		
1: Deposit the HTL material onto the perovskite layer using spin-coating.	2: Deposit the metal electrode (gold) onto the hole transport layer using thermal evaporation to form a conductive contact for the solar cell.	3: Complete device obtained

Electron Transport Layer (ETL) Preparation: The fabrication process begins with the preparation of the Electron Transport Layer (ETL), which is crucial for facilitating the movement of electrons from the perovskite layer to the electrode while preventing the recombination of electrons and holes. This step involves creating a solution of tin oxide (SnO2) due to its excellent electron extraction properties and stability. The SnO2 solution is spin-coated onto a substrate and then annealed at high temperatures to form a thin, uniform layer. This thin layer ensures efficient electron transfer to the electrode, reducing energy losses and enhancing the overall efficiency and stability of the device.

Perovskite Layer (PVKL) Preparation: Following the ETL preparation, the focus shifts to the perovskite layer, which is the core of the device responsible for light absorption and the generation of charge carriers (electrons and holes). The process involves dissolving lead iodide (PbI2) and an organic salt in a solvent to create a precursor solution. This solution is then deposited onto the ETL. The deposition is followed by a two-step annealing process: initially at a lower temperature to form a lead iodide film and subsequently at a higher temperature after applying an organic solution to convert the film into the perovskite structure. This controlled temperature and solution composition are critical for forming a high-quality perovskite layer with optimal photovoltaic properties.

Hole Transport Layer (HTL) Preparation and Electrode Plating: The final fabrication steps involve preparing the Hole Transport Layer (HTL) and plating the electrodes. The HTL is designed to collect holes (positive charge carriers) from the perovskite layer and transport them to the electrode, thus complementing the ETL by ensuring efficient charge separation and collection. The HTL is prepared by dissolving an organic semiconductor material in a solvent and depositing it onto the perovskite layer. After HTL deposition, electrodes are plated onto the HTL to complete the device's electrical circuit. This step often involves thermal evaporation or sputtering of metals to form a thin conductive layer, which efficiently collects and transports charge carriers out of the device, ensuring optimal electrical performance.

3. Results and Discussions

Absorption Spectroscopy (Abs): Absorption spectroscopy quantifies the light absorbed by perovskite materials across various wavelengths, providing essential data on optical properties and bandgap energy. In Figure 1(A), the typical absorption spectrum could be found in a classical fabrication strategy using MA accompanied with thermal annealing, while a featureless character was found when thermal annealing was not adopted (Figure 1(B). Therefore, in most common strategies, thermal

DOI: 10.54254/2755-2721/124/2025.20002

annealing is required for a well-formed crystal. In our method, a new solvent was adopted, compared with Figure 1(C) & (D), it could be found that, comparable absorption could be observed, indicating a well build perovskite crystal.

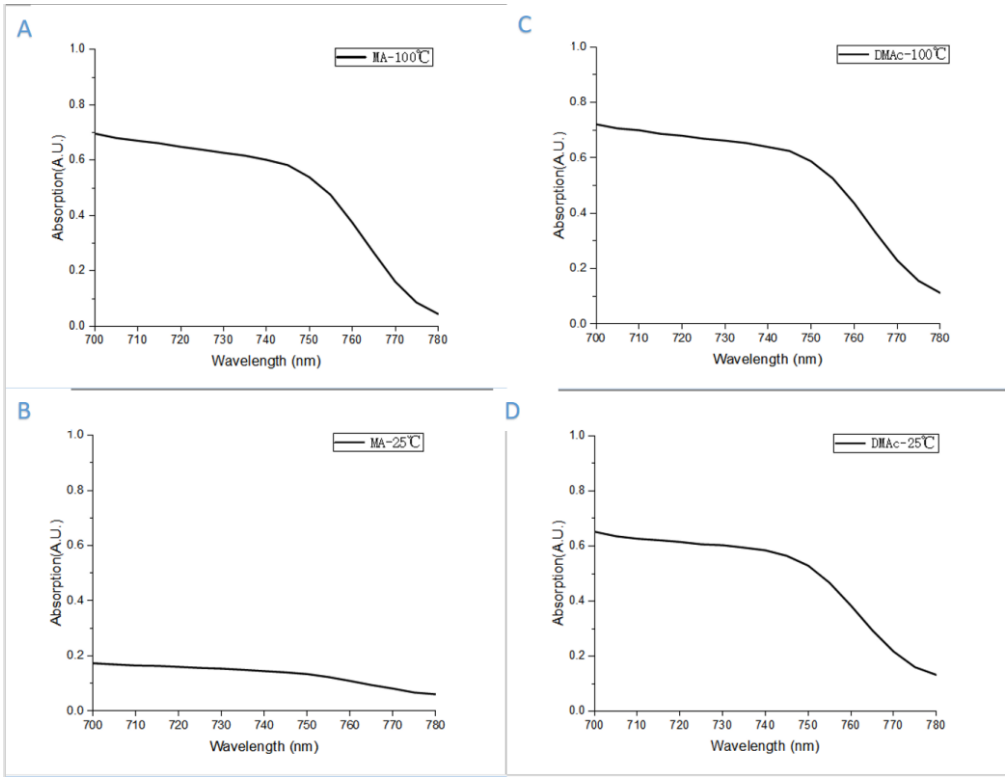


Figure 1: Absorption spectrum of perovskite films fabricated under 100 °C with MA (A) DMAc(B), and at room temperature with MA(C) and DMAc(D).

The absorption curve for low-temperature fabricated perovskite (DMAc-RoomTemperature) shows only a 0.06 difference in maximum absorption value compared to high-temperature fabricated perovskite (DMF-100°C). Absorbance drops by over 60% at 730 nm for DMAc-RoomTemperature and at 740 nm for DMF-100°C, indicating a minimal 10 nm difference, proving similar performance in absorption.

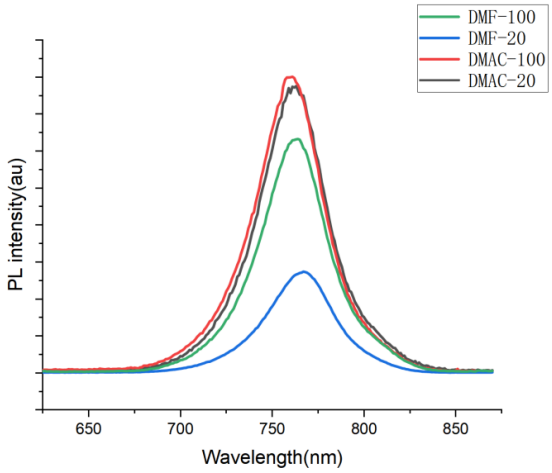


Figure 2: Photoluminescence spectra of perovskite films.

DOI: 10.54254/2755-2721/124/2025.20002

In order to evaluate the trap state properties of the perovskite film, photoluminescence (PL) was measured. Photoluminescence spectroscopy examines the emitted light from perovskite materials, providing insights into material quality and recombination properties. PL performance of perovskite samples fabricated using DMF and DMAC solvents reveals notable differences. For DMF-fabricated samples, the DMF-100 sample shows a peak PL intensity of approximately 1.25 arbitrary units (au) at around 760 nm, while the DMF-20 sample displays a lower peak intensity of about 0.75 au. In contrast, DMAC-fabricated samples demonstrate superior PL performance, with the DMAC-100 sample exhibiting a peak intensity of around 1.35 au at 760 nm and the DMAC-20 sample showing a strong peak intensity of approximately 1.15 au. Comparatively, DMAC solvents result in higher PL intensities than DMF solvents under both high and low-temperature conditions, indicating more efficient trap state passivation and better overall material quality. The data underscores the efficacy of DMAC in producing perovskite films with enhanced photoluminescence properties, regardless of the fabrication temperature. The PL intensity for perovskites fabricated using DMAc solvents surpasses those fabricated using DMF solvents, with less than a 5% difference between high and low-temperature fabricated samples, indicating consistent material quality across different processing conditions. A weak emission indicates a low luminescence efficiency, which might be associated with numerous intermediate trap states. The introduction of a new solvent, such as DMAC, enhances the trap state passivation ability by effectively reducing the number of defects within the perovskite film. This improvement is significant because it allows for strong PL to be observed even in the absence of annealing processes. Consequently, the new solvent not only mitigates the effects of intermediate trap states but also ensures high material quality and performance, highlighting its potential for scalable and efficient perovskite solar cell production.

X-ray Diffraction (XRD): X-ray diffraction characterizes the crystallographic structure, phase purity, and orientation of perovskite films. The XRD graph shows distinct peaks at specific 2θ angles, indicating well-defined crystalline structures across all samples. Sharp peaks suggest minimal microstrain and large crystallite sizes, reflecting high-quality films with low structural defects under various conditions.

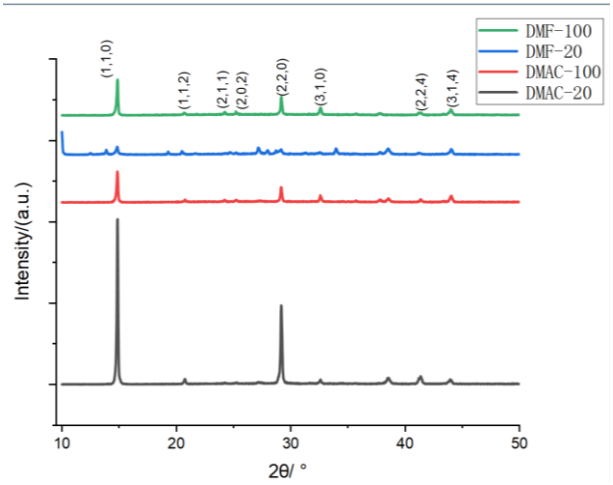


Figure 3: XRD patterns of perovskite films.

Figure 3 shows that DMF-fabricated samples, especially DMF-100, have prominent peaks at various planes, indicating high crystallinity. However, DMF-20 displays weaker peaks, suggesting lower crystallinity at reduced temperatures. On the other hand, DMAC-fabricated samples have strong and well-defined peaks, with DMAC-100 showing slightly higher intensities than DMF-100, which points to better crystalline quality. Interestingly, DMAC-20 maintains peak intensities

DOI: 10.54254/2755-2721/124/2025.20002

comparable to DMAC-100, indicating that DMAC solvent supports high crystalline quality even at low temperatures. Additionally, Full Width Half Maximum (FWHM) analysis reveals that DMAC samples have narrower peak widths, indicating larger crystallite sizes and fewer defects. Overall, the XRD and FWHM data suggest that DMAC solvents produce perovskite films with superior crystalline properties, larger crystallite sizes, and fewer defects across different temperatures, making them more effective for high-quality perovskite film fabrication.

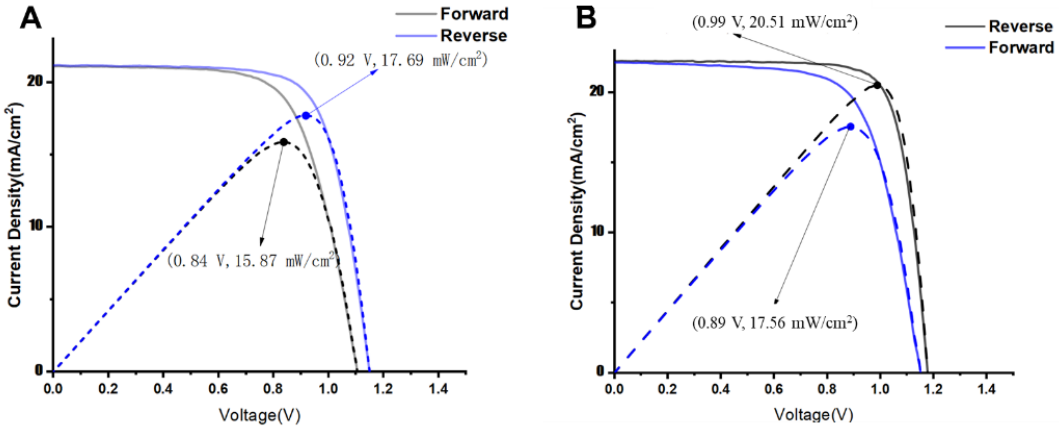


Figure 4: Current density (J) and Voltage (V) characterization of perovskite devices fabricated under 100 °C with MA for control (A) and DMAc(B).

The analysis of the J-V curves reveals differences between control and low-temperature processed samples. Control samples exhibit open-circuit voltages (Voc) from 0.84 V to 0.97 V and short-circuit current densities (Jsc) from 17.51 mA/cm² to 19.30 mA/cm², with notable hysteresis indicating charge trapping. Low-temperature samples show higher Voc up to 1.00 V and Jsc up to 20.51 mA/cm², with improved fill factors and power conversion efficiencies (PCE) up to 20.51 %. The PCE was calculated according to the definition below:

$$PCE = (J_{SC} \cdot V_{OC} \cdot FF)/(P_{in}) \quad (1)$$

Where FF represents the fill factor, and Pin represents the input power density which is usually 100 mW/cm2. Reduced hysteresis suggests improved charge transport and stability, reflecting superior material quality and device performance.

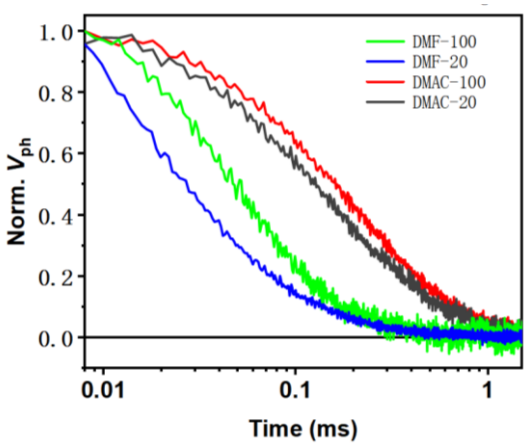


Figure 5: Transient photovoltage decay dynamics of perovskite devices.

DOI: 10.54254/2755-2721/124/2025.20002

Transient Photovoltage (TPV): Transient photovoltage measurements analyze the dynamics and lifetimes of charge carriers within the perovskite solar cells, providing crucial information on the efficiency of charge separation and transport processes, which are key factors in determining overall device performance. The TPV graphs (Figure 5) demonstrate significant differences between MA and DMAC-based perovskites under varying fabrication temperatures. For MA perovskites, high-temperature samples (DMF-100) show a strong initial response and slower decay, indicating efficient charge separation and slower recombination, with normalized voltage Vph remaining above 0.6 at 0.01 ms. In contrast, low-temperature samples (DMF-20) exhibit a much faster decay, with Vph dropping below 0.4 at 0.01 ms, indicating poor charge carrier lifetimes. DMAC-based perovskites show stable charge carrier dynamics regardless of temperature, with both high-temperature (DMAC-100) and low-temperature (DMAC-20) samples exhibiting similar decay profiles, maintaining Vph above 0.5 at 0.01 ms. In most common cases, the charge carrier decay dynamics of the selected samples could be described by an exponential process, while the DMAC devices would like to be poly-exponential, in which their apparent decay dynamics could be described as follows:

$$\tau = \frac{A_1\tau_1 + A_2\tau_2}{A_1 + A_2} \quad (2)$$

Where Ai is the pre-exponential factors represents the component intensity, tI is the decay component, and t is the apparent decay lifetime. The significant difference in charge carrier dynamics due to fabrication temperature impacts the performance of perovskite solar cells. MA perovskites fabricated at low temperatures (DMF-20) show reduced efficiency and shorter charge carrier lifetimes, leading to lower overall device performance, as indicated by the rapid TPV decay. In contrast, DMAC-based perovskites maintain high performance at low temperatures, with comparable charge carrier lifetimes and stability to high-temperature samples. This suggests that DMAC-based perovskites are more suitable for low-temperature processing, enhancing scalability, reducing manufacturing costs, and broadening application possibilities for perovskite solar cells.

4. Conclusions

In conclusion, the analysis of perovskite solar cells (PSCs) fabricated with DMF and DMAc solvents at various temperatures underscores the superiority of DMAc for low-temperature processes. DMF-fabricated samples demonstrate reasonable performance; DMF-100 samples exhibit high crystallinity with prominent X-ray diffraction (XRD) peaks, while DMF-20 samples show reduced crystallinity. Photoluminescence (PL) measurements for DMF-100 display a peak intensity of approximately 1.25 arbitrary units (au), but this reduces to about 0.75 au for DMF-20, indicating poorer material quality and higher defect densities at lower temperatures. In contrast, DMAc-fabricated samples consistently outperform their DMF counterparts, with DMAc-100 samples showing stronger XRD peaks and DMAc-20 samples maintaining high PL performance with peak intensities of around 1.15 au, nearly comparable to the 1.35 au of DMAc-100. Full Width Half Maximum (FWHM) analysis confirms that DMAc samples have narrower peak widths, reflecting larger crystallite sizes and fewer defects. J-V curve analysis further shows that low-temperature DMAc-processed samples achieve higher open-circuit voltages (Voc), short-circuit current densities (Jsc), improved fill factors, and power conversion efficiencies (PCE), with reduced hysteresis, indicating superior charge transport and stability. Collectively, these results demonstrate that DMAc solvents enable the production of high-quality perovskite films at low temperatures, surpassing the performance of DMF-fabricated samples and highlighting DMAc's potential for scalable and efficient PSC manufacturing.

DOI: 10.54254/2755-2721/124/2025.20002

Acknowledgments

First of all, I would like to thank my supervisors Mr Ramsby for his invaluable guidance and support throughout this research. Also thanks to Dr Wang for technical revisions and insightful suggestions provided on my paper. Thanks also go out to my parents for their constant push that made it easy for me strive until the end. Their encouragement to attend was a large part of what led me here today.

References

[1] *Ono, L. K., et al.,Reducing Detrimental Defects for High-Performance Metal Halide Perovskite Solar Cells, Angewandte Chemie International Edition 2020, 59 (17), 6676-6698.*
[2] *Zhu, T., et al.,Ultrafast Dynamic Microscopy of Carrier and Exciton Transport, Annu. Rev. Phys. Chem. 2019, 70, 219-244.*
[3] *Kojima, A., et al.,Organometal Halide Perovskites as Visible-Light Sensitizers for Photovoltaic Cells, J. Am. Chem. Soc. 2009, 131 (17), 6050-6051.*
[4] *Lee, M. M., et al.,Efficient Hybrid Solar Cells Based on Meso-Superstructured Organometal Halide Perovskites, Science 2012, 338 (6107), 643-647.*
[5] *Chen, Q., et al.,Planar Heterojunction Perovskite Solar Cells Via Vapor-Assisted Solution Process, J. Am. Chem. Soc. 2014, 136 (2), 622-625.*
[6] *Meng, L., et al.,Recent Advances in the Inverted Planar Structure of Perovskite Solar Cells, Acc. Chem. Res. 2016, 49 (1), 155-65.*
[7] *Zheng, Y., et al., Towards 26% efficiency in inverted perovskite solar cells via interfacial flipped band bending and suppressed deep-level traps. Energy & Environmental Science, 2024, 17(3), 1153–1162.*
[8] *Sidhik, S., et al.,Improving the Optoelectronic Properties of Mesoporous TiO2 by Cobalt Doping for High-Performance Hysteresis-Free Perovskite Solar Cells, ACS Appl. Mater. Interfaces 2018.*
[9] *Xue, R., et al.,Molecular Design with Silicon Core: Toward Commercially Available Hole Transport Materials for High-Performance Planar P-I-N Perovskite Solar Cells, J. Mater. Chem. A 2018, 6 (2), 404-413.*
[10] *Zhang, S., et al.,Minimizing Buried Interfacial Defects for Efficient Inverted Perovskite Solar Cells, Science 2023, 380 (6643), 404-409.*
[11] *De Bastiani, M., et al.,Efficient Bifacial Monolithic Perovskite/Silicon Tandem Solar Cells Via Bandgap Engineering, Nature Energy 2021, 6 (2), 167-175.*
[12] *Dunlap-Shohl, W. A., et al.,Synthetic Approaches for Halide Perovskite Thin Films, Chemical Reviews 2019, 119 (5), 3193-3295.*
[13] *Bati, A. S. R., et al.,Next-Generation Applications for Integrated Perovskite Solar Cells, Communications Materials 2023, 4 (1).*