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Editorial: Emerging thin-film solar cell research

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Editorial on the Research Topic
Emerging thin-film solar cell research

Thin-film photovoltaics, particularly those based on perovskite materials, are revolutionizing solar energy research through rapid efficiency gains, innovative device architectures, and advanced modeling techniques. This Research Topic, *Advances in Thin Film Photovoltaics for Solar Energy Conversion*, presents six original contributions that address critical challenges in device performance, stability, scalability, and characterization. Spanning interfacial engineering, tandem structures, novel deposition methods, and sophisticated modeling, these studies offer cutting-edge insights and methodologies to overcome key barriers in thin-film solar cell development, with a focus on perovskite and related technologies.

The objective of this Research Topic is to highlight innovative strategies that enhance the efficiency, reproducibility, and manufacturability of thin-film photovoltaic devices. Achieving commercial viability requires precise control over material deposition, optimized interfacial alignment, robust modeling for performance diagnostics, and a deep understanding of defect-related phenomena. The contributions in this Research Topic tackle these challenges through a blend of experimental and theoretical approaches, providing a comprehensive perspective on the future of thin-film photovoltaics.

Belmahdi et al. focus on parameter extraction for photovoltaic modules, presenting a comparative analysis of six analytical and numerical methods based on the single diode model (SDM) (Belmahdi et al.). These methods, developed by Khan et al., Blas et al., Phang et al., Vika, Cubas et al., and Almonacid et al., are evaluated under standard test conditions, with a focus on maximum power point current and voltage. The study demonstrates that the Phang et al. approach excels in predicting photocurrent-voltage (I-V) and power-voltage (U-V) curves, achieving lower errors (e.g., root mean square error, mean bias error, normalized RMSE, mean absolute percentage error, and absolute error) compared to other methods, particularly Almonacid et al., which underestimates the I-V curve at maximum power. This work establishes a robust framework for performance diagnostics, applicable to both conventional and perovskite-based modules, enhancing the accuracy of module characterization.

Brown and Li provide a comprehensive review of carbon-based perovskite solar cells (PSCs), which offer cost-effectiveness, simplified production, and enhanced stability compared to devices with metallic electrodes (Brown and Li). Their analysis highlights the critical challenge of poor contact quality at the carbon/perovskite interface, which limits device performance. By examining strategies such as chemical passivation and interface modification, the review outlines a roadmap for improving efficiency and scalability. These advancements position carbon-based PSCs as a promising direction for commercial development, addressing key barriers to widespread adoption of perovskite technologies.

Menon and Yan explore four-terminal (4T) perovskite-cadmium telluride (CdTe) tandem solar cells, combining SCAPS simulation with experimental validation (Menon and Yan). Their simulations demonstrate a power conversion efficiency (PCE) exceeding 23%, confirming the architecture's feasibility. Experimentally, they achieve tandem efficiencies of 18.2% and 19.4% by pairing wide-bandgap perovskite cells (1.6 eV and 1.77 eV) with a narrow-bandgap CdTe cell (1.5 eV). The 1.77 eV perovskite proves more suitable for optimal spectral utilization, highlighting the potential of 4T tandems to surpass single-junction efficiency limits while leveraging mature CdTe technology. This work underscores the importance of device architecture engineering for next-generation photovoltaics.

Munoz-Diaz et al. investigate hysteresis in $MAPbI_3$-based devices, comparing a 15% efficient PSC to a memristor lacking directional photocurrent (Munoz-Diaz et al.). Using current-voltage curves and impedance spectroscopy, they identify a significant inverted hysteresis effect at forward bias, attributed to a chemical inductor component in the equivalent circuit. Their findings classify electrical responses based on recombination in selective-contact devices and voltage-activated conduction in symmetric-contact devices. By establishing a link between PSC and memristor behavior, this study highlights the multifunctional potential of perovskites in energy and memory applications, while raising critical questions about long-term stability due to ion migration and trap states.

Moser et al. advance the understanding of $(Cs_{0.07}FA_{0.93})PbI_3$ perovskite film formation through a two-step vapor deposition process. An inorganic CsI/PbI_2 precursor stack is deposited via thermal evaporation, followed by chemical vapor deposition (CVD) with formamidinium iodide (FAI) (Moser et al.). Their study reveals that substrate surface properties and thermal treatment during the initial CVD phase significantly influence precursor crystallinity and morphology. Cesium diffusion through PbI_2 ensures uniform elemental composition, enhancing film quality. These insights provide a foundation for scalable, high-quality perovskite films, critical for industrial applications of thin-film photovoltaics.

Fru et al. explore compositional tuning in $MAPb(I_{1-x}Br_x)_3$ thin films prepared by sequential physical vapor deposition of $MAPbBr_3$ on $MAPbI_3$ (Fru et al.). By varying MABr thickness (300–500 nm), they achieve bandgaps from 2.21 to 2.14 eV, with bromine content (x = 0.89–0.95) decreasing as thickness increases. X-ray diffraction confirms a structural transition from tetragonal $MAPbI_3$ to cubic-like $MAPbBr_3$, accompanied by improved grain size (150–320 nm) and charge carrier mobility. Device PCEs range from 0.56% ($MAPbBr_3$) to 1.15% ($MAPbI_3$), with Mott-Schottky analysis revealing a built-in voltage of 1.6 V in bromine-rich films compared to 0.7 V in MAPbI3 devices. This work underscores the role of compositional control in optimizing optoelectronic properties for tailored solar harvesting applications.

The current state and future directions of thin-film photovoltaics are listed below:

1. Advanced Characterization and Modeling: The integration of analytical and numerical methods, as demonstrated by Belmahdi et al., enables precise parameter extraction, enhancing device design and diagnostics across both perovskite and conventional modules.
2. Deposition Engineering: Vapor-based deposition techniques, explored by Moser et al. and Fru et al., highlight the importance of controlling crystallinity, morphology, and composition for high-quality thin films, critical for scalability.
3. Interface and Compositional Control: Interface optimization (Brown and Li) and compositional tuning (Fru et al.) are pivotal for improving efficiency and stability, addressing key challenges in device performance.
4. Interdisciplinary Applications: Studies like Munoz-Diaz et al. and Menon and Yan extend the relevance of perovskites, connecting to memristive technologies and hybrid tandem systems, broadening their impact in electronics and photovoltaics.

Collectively, these articles strengthen our understanding of thin-film photovoltaic materials and devices, from material synthesis to device architecture. They highlight critical research directions, including improving long-term operational stability, developing scalable deposition processes, and integrating thin-film technologies with complementary systems. The focus on modeling, as seen in Belmahdi et al. and Menon and Yan, underscores the importance of theoretical frameworks in guiding experimental advancements, ensuring that thin-film photovoltaics can meet the demands of commercial applications.

We express our deepest gratitude to the authors for their outstanding contributions. We also thank the reviewers for their rigorous and insightful evaluations, which significantly enhanced the quality of this Research Topic. The collaborative efforts of the editorial and production teams were instrumental in bringing this Research Topic to fruition. We hope these insights will inspire and guide future advancements, as the global research community continues to drive innovation in thin-film photovoltaics for sustainable solar energy conversion.

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