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An Overview on Printing Technologies of Large-Scale Perovskite Solar Cells

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Extended Abstract

Introduction

The rapid growth in global energy demand and the environmental consequences of fossil fuel consumption have intensified the search for sustainable and low-carbon energy technologies. Among renewable energy sources, solar energy stands out due to its abundance, scalability, and long-term potential for mitigating greenhouse gas emissions. Although crystalline silicon solar cells dominate the photovoltaic market with power conversion efficiencies (PCEs) exceeding 20%, their relatively high manufacturing cost and energy-intensive processing motivate the development of alternative photovoltaic technologies.

Metal halide organic–inorganic perovskites (OMHPs) have emerged as highly promising absorber materials for next-generation solar cells owing to their low exciton binding energy, high absorption coefficient, long carrier diffusion lengths, and solution processability at low temperatures. Since their first demonstration in 2009, perovskite solar cells (PSCs) have achieved a remarkable increase in PCE from 3.8% to over 26%, surpassing the Shockley–Queisser limit in tandem configurations with silicon. However, these record efficiencies are typically obtained on small-area devices (<1 cm^2), whereas commercial deployment requires large-area, scalable, and cost-effective fabrication methods.

Conventional spin-coating, despite its success in laboratory-scale PSC fabrication, suffers from poor material utilization, limited reproducibility, and severe non-uniformity when applied to large substrates. Consequently, scalable printing and coating technologies have attracted significant attention as viable routes toward industrial-scale production of high-performance PSCs. This review focuses on recent advances in printing-based fabrication techniques for large-area perovskite solar cells, emphasizing their processing mechanisms, performance achievements, and remaining challenges.

Methodology

This work presents a comprehensive and systematic review of state-of-the-art printing and scalable coating technologies employed in the fabrication of perovskite solar cells and modules. The surveyed techniques include blade coating, slot-die coating, spray coating, flexographic printing, gravure printing, screen printing, and inkjet printing. Each method is analyzed in terms of its operating principles, process parameters, material compatibility, and suitability for roll-to-roll and large-area manufacturing.

Special attention is given to the deposition of key functional layers, including the perovskite absorber, electron transport layers (ETLs), hole transport layers (HTLs), and electrodes. Reported strategies for controlling film morphology, crystallization dynamics, solvent evaporation, and interfacial engineering are discussed. Performance metrics such as power conversion efficiency, active area, module scalability, and operational stability are compared across different printing techniques based on reported experimental results.

Results and Discussion

The reviewed studies demonstrate that printing-based fabrication techniques have enabled substantial progress toward scalable and high-performance PSCs. Blade coating and slot-die coating have emerged as leading methods for large-area perovskite deposition, achieving PCEs exceeding 20% on small-area devices and over 15% on modules larger than 50 cm^2. Innovations such as meniscus-guided coating, surfactant-stabilized inks, substrate preheating, and additive engineering have significantly improved film uniformity and crystallinity.

Spray coating has shown strong potential for low-temperature, large-area processing, with reported efficiencies approaching 19% and excellent compatibility with flexible substrates. Screen printing remains the dominant technique for fabricating mesoporous PSC architectures and carbon-based electrodes, offering exceptional long-term stability and scalability, including modules exceeding 100 cm² with operational lifetimes over 10,000 hours. Inkjet printing provides unparalleled control over film thickness and patterning, enabling digital, mask-free fabrication with minimal material waste. Recent advances in ink formulation and thermal-assisted printing have pushed inkjet-printed PSC efficiencies beyond 20%. In contrast, flexographic and gravure printing offer very high throughput and roll-to-roll compatibility but remain challenged by ink rheology constraints, resolution limitations, and perovskite film uniformity, resulting in comparatively lower device efficiencies.
Overall, printing technologies have demonstrated the feasibility of producing efficient, stable, and large-area perovskite solar cells, although performance gaps with spin-coated laboratory devices persist.

Conclusion

Printing-based fabrication represents a critical pathway toward the commercialization of perovskite solar cells. Despite remarkable progress, several challenges remain, including precise control of crystallization kinetics, solvent management without toxic antisolvents, ink stability, defect passivation, and long-term environmental stability of printed films. Moreover, the integration of printing techniques into continuous roll-to-roll manufacturing lines requires further optimization of process windows and equipment design.
Future research should focus on the development of environmentally benign inks, universal printing-compatible charge transport materials, and hybrid manufacturing approaches that combine printing with vacuum-based or vapor-phase techniques. Tandem architectures, particularly perovskite–silicon and perovskite–chalcogenide systems, are expected to benefit significantly from scalable printing methods. With continued interdisciplinary efforts in materials science, process engineering, and device physics, printing technologies are poised to play a transformative role in enabling low-cost, high-efficiency, and industrial-scale perovskite photovoltaics.

Keywords: Perovskite Solar Cells, Printing Technologies, Spray Coating, Flexographic Printing, Inkjet Printing.

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