How Your PVD System Determines Perovskite Solar Cell Film Quality

Perovskite photovoltaics have moved from a laboratory curiosity to a genuine commercial contender in under two decades. Certified single-junction efficiencies have now reached 27%, whilst perovskite-silicon tandem configurations have surpassed 34%, with LONGi Green Energy holding the current NREL-certified world record at 34.85% as of April 2025[1].

Behind those numbers sits a deceptively straightforward question that process engineers continue to wrestle with, how do you reliably deposit a perovskite absorber that performs at its theoretical best, across an area large enough to matter commercially? Physical vapour deposition (PVD) sits at the centre of that conversation not only for the perovskite layer itself, but for the transparent electrodes and carrier transport layers that bracket it. Understanding what the deposition system contributes, and what it can compromise, is the foundation of everything that follows in device fabrication.

What PVD Brings to Perovskite Fabrication

Perovskites are potentially processable from solution. The two most popular routes in academic research, spin-coating and slot-die coating benefit from accessible equipment and quick optimisation cycles [2]. Vapour-phase deposition techniques, however, offer advantages that solution processing cannot readily replicate: a solventless approach, conformal coating over textured substrates, and precise control of layer composition and thickness without the crystallisation problems associated with solvent-based methods [3].

Thermal co-evaporation is currently the most studied PVD route for the perovskite absorber itself. In this process, lead iodide (PbI_2) and an organic halide source, most commonly formamidinium iodide (FAI) or methylammonium iodide (MAI) are evaporated simultaneously from separate crucibles inside a high-vacuum chamber. The vapour fluxes combine at the substrate surface, where they react and crystallise into the perovskite phase. The critical variable is the ratio of those two fluxes, which must be held within a tight window to achieve stoichiometric films. Deviations produce either lead-rich films with residual PbI_2 or organic-rich films with disordered crystallisation both of which introduce non-radiative recombination pathways that suppress open-circuit voltage and fill factor. [3], [4]

How Does Substrate Temperature Affect Perovskite Crystal Grain Structure?

The impact of deposition system parameters on device performance is clearly illustrated by the role of substrate temperature during co-evaporation. Research published in ACS Energy Letters demonstrated that substrates cooled to −2°C produced micrometre-sized crystals, whereas substrates held at room temperature (23°C) yielded films comprising crystals of approximately 100 nm [4]. Solar cells fabricated from the larger-grain films achieved efficiencies of up to 18.2%, with substrate temperature identified as the key parameter governing the rate of organic precursor adsorption and the subsequent conversion from PbI_2 to the perovskite phase.

This is not a minor observation. Grain boundaries are directly correlated with recombination losses: a higher boundary density generates trapping sites that reduce carrier lifetime [5]. High-quality perovskite thin films with large grain sizes, low defect density, and consistent morphology support efficient carrier mobility by minimising non-radiative recombination and extending carrier diffusion lengths [6]. The ability of the deposition system to maintain consistent substrate temperatures uniformly across the entire substrate area is therefore a primary performance variable, not a secondary one.

Stoichiometric Control and the Role of Deposition Rate

The stoichiometric accuracy of co-evaporation depends on independent, stable control of the flux rate from each source. Organic halide sources have substantially higher vapour pressures than inorganic precursors, making their flux more sensitive to small temperature fluctuations at the source crucible. Even minor variations in crucible temperature produce compositional gradients through the thickness of the film. A comprehensive review of vapour deposition approaches confirms that stoichiometric accuracy and crystallisation dynamics are both central to solar cell efficiency, and that their simultaneous control remains the primary challenge of vapour processing [3]

Fast co-evaporation targeting industrially relevant deposition rates introduces a further dimension. Deposition rates sufficient to produce 1 µm thick layers in under 50 minutes have been demonstrated, with devices fabricated using optimised fast co-evaporation achieving power conversion efficiencies (PCEs) above 19% [4]. This demonstrates that fast co-evaporation is viable for industry-scale production, if temperature and substrate parameters are precisely managed. From an equipment standpoint, this requires a deposition tool capable of maintaining stable, independently regulated fluxes from multiple sources across extended runs.

Sputtering and the Plasma Damage Problem

PVD's role in perovskite device fabrication extends beyond the absorber layer. Transparent conductive oxides (TCOs) such as indium tin oxide (ITO) and indium zinc oxide (IZO) are routinely deposited by magnetron sputtering to serve as the top transparent electrode in semi-transparent and tandem cell configurations. The plasma environment used in sputtering introduces a known risk of damage to the underlying perovskite stack.

Specifically, Härtel et al. identified ion bombardment, rather than plasma radiation, as the primary damage mechanism when sputtering TCOs onto perovskite/C_{60} stacks [7]. This mechanistic distinction is significant because it points to process parameters specifically sputter power density and working pressure as the variables to manage. A separate study demonstrated that reducing sputter power, as a direct process modification, was sufficient to reduce damage-induced non-radiative recombination losses and improve device performance without compromising the optical or electrical quality of the deposited IZO film [8]. The authors validated this 'soft sputtering' approach on perovskite top cells without a protective SnO_2 buffer layer.

Where damage cannot be fully suppressed by process adjustment alone, buffer layers provide an engineering solution. An ultrathin (<10 nm) evaporated layer of vanadium oxide or molybdenum oxide, placed atop the hole-transport layer before ITO deposition, has been shown to effectively prevent sputtering damage in semi-transparent perovskite devices [9]. A 2024 review confirmed that both process optimisation and material strategies are active and productive lines of investigation, and that the choice of deposition system directly determines which approaches are available to the process engineer [10].

Why System Architecture Matters while scaling up

The transition from laboratory-scale spin-coated devices to commercially relevant modules has exposed the limits of solution processing for uniform large-area coverage. PVD methods, by contrast, are well-established in the wider thin-film photovoltaics industry in CdTe and CIGS manufacturing and bring with them a body of equipment knowledge that is directly applicable to perovskite. A 2024 review in Energy & Environmental Science noted that vapour processing of perovskite materials is now backed by a significant number of tool manufacturers who have been commercialising production-line-ready tools, with several stating market entry from 2024 onwards [2].Most solar module manufacturers had, at that point, set commercialisation dates for first products from 2025.

Single-source thermal evaporation in which a pre-mixed perovskite powder is evaporated from a single crucible offers a simplified route to stoichiometric transfer with high phase purity. Research on single-source PVD of $CH_3NH_3PbI_3$ confirmed excellent compositional transfer from source powder to deposited film, with no residual MAI or PbI_2 phases and a well-defined grain structure [11]. This approach removes the challenge of independently stabilising two flux sources, though it introduces constraints around precursor powder preparation and thermal stability of the mixed material in the crucible. The choice between single-source and multi-source co-evaporation therefore depends on the target composition and the level of bandgap tunability required factors that feed directly back into the specification of the deposition system.

Machine learning frameworks are beginning to assist in mapping the multi-dimensional parameter space of vapour deposition processes. One 2025 study achieved a coefficient of determination of 0.9464 for PCE prediction using an ETree model trained on vapour-deposited perovskite device data [3]. Such tools accelerate optimisation, but they work from data that the deposition system itself generates. A system with poor process stability or limited sensor feedback produces data that undermines the modelling effort. Reliable deposition hardware remains the prerequisite.

For tandem architectures, where thermally co-evaporated perovskites are integrated with silicon or additional perovskite sub-cells, compositional control becomes even more demanding. Work published in 2025 demonstrated a current-matched monolithic all-perovskite triple-junction device fabricated using optimised thermal co-evaporation of multiple absorber layers with distinct bandgaps [12]. The top and middle sub-cells were produced by co-evaporation of $Cs_{0.3}FA_{0.7}Pb(I_{0.56}Br_{0.44})_3$ and $FAPbI_3$ respectively, with the deposition system providing the compositional resolution needed to hit specific bandgap

targets. This is a clear illustration of the relationship between system capability and device architecture: a deposition platform with limited compositional control forecloses certain tandem configurations before the device design process has even begun.

Specific areas where the deposition system determines the outcome:

- Independent flux stability and control in co-evaporation
- Substrate temperature uniformity and precision across large areas
- Sputter power density management for TCO deposition without absorber damage
- Chamber geometry that supports conformal coverage on textured substrates for tandem integration

Why Choose Nikalyte for Perovskite PVD Research and Development?

The research reviewed above defines a clear set of equipment requirements: independent flux stability in co-evaporation, precise and uniform substrate temperature control, managed sputter power density for TCO deposition, and chamber geometry supporting conformal coverage on textured substrates. Nikalyte's PVD systems are designed to meet exactly these demands.

The NEXUS ultra-high vacuum PVD system operates at base pressures below 5×10^{-7} Torr, providing the contamination-free deposition environment required for high-purity perovskite absorber and transport layer films. Its confocal port geometry accommodates up to five sources simultaneously, supporting the multi-source co-evaporation configurations described in the literature above. Substrate heating, rotation, and RF/DC biasing are integrated within the same vacuum environment, enabling the substrate temperature control that the published grain-size data demonstrates is critical to device efficiency. The optional load-lock configuration preserves base pressure stability across the extended sequential deposition runs required for multi-layer perovskite stacks. [13]

For TCO electrode deposition, Nikalyte's Stellar UHV magnetron sputter sources support both DC and RF operation, accommodating the full range of electrode target materials. The Tri-Stellar triple-target sputter source enables multi-target co-sputtering within a single vacuum run, whilst bakeable UHV-compatible designs maintain base pressure stability across extended processes. Where soft-sputtering approaches are required to protect the perovskite stack from ion bombardment damage, the independently controlled sputter power settings on Nikalyte sources provide the process parameter resolution needed to implement them. [14]

For research groups and process engineers moving from laboratory-scale fabrication towards device optimisation or tandem integration, Nikalyte's modular system architecture means capability can be scaled and reconfigured as the process demands evolve. Explore the full range of Nikalyte PVD systems or contact the team to discuss your specific deposition requirements.

Conclusion

Perovskite photovoltaics have arrived at a point where the materials science is sufficiently understood for manufacturing conversations to be productive. Film quality its grain structure, stoichiometry, surface coverage, and freedom from plasma-induced damage does not emerge from the perovskite material alone. It emerges from the perovskite material processed through a deposition system that is matched to the demands of the application.

Contact us to discuss how Nikalyte's PVD systems can support precise film deposition for your perovskite photovoltaic research and device development.

References

1. National Renewable Energy Laboratory. (2025). Best Research-Cell Efficiency Chart. Retrieved May 2026, from https://www.nrel.gov/pv/cell-efficiency.html
2. Khenkin, M. V., et al. (2024). Vapor phase deposition of perovskite photovoltaics: short track to commercialization? Energy & Environmental Science. https://doi.org/10.1039/D3EE03273F
3. Luo, L., Gao, Z., Fang, M., Shen, Y., Chen, S., Bu, Y., Gu, J., Hu, C., & Ding, J. (2025). Accelerated development of vapor deposition technology for efficient perovskite solar cells via accurate and practical machine learning tools. Advanced Science, 2510946. https://doi.org/10.1002/advs.202510946
4. Piot, M., Alonso, J. E. S., Zanoni, K. P. S., Rodkey, N., Ventosinos, F., Roldán-Carmona, C., Sessolo, M., & Bolink, H. J. (2023). Fast coevaporation of 1 µm thick perovskite solar cells. ACS Energy Letters, 8(11), 4711–4713. https://doi.org/10.1021/acsenergylett.3c01724
5. Chu, Z., Yang, M., Schulz, P., Wu, D., Ma, X., Seifert, E., Sun, L., Li, X., Zhu, K., & Lai, K. (2017). Impact of grain boundaries on efficiency and stability of organic-inorganic trihalide perovskites. Nature Communications, 8, 2230. https://www.nature.com/articles/s41467-017-02331-4
6. Li, X., et al. (2024). Key advancements and emerging trends of perovskite solar cells in 2024–2025. Nano-Micro Letters. https://doi.org/10.1007/s40820-025-02022-6
7. Yang, Q., Duan, W., Eberst, A., Klingebiel, B., Wang, Y., Kulkarni, A., Lambertz, A., Bittkau, K., Zhang, Y., Vitusevich, S., Rau, U., Kirchartz, T., & Ding, K. (2024). Origin of sputter damage during transparent conductive oxide deposition for semitransparent perovskite solar cells. Journal of Materials Chemistry A, 12, 14816–14827. https://doi.org/10.1039/D3TA06654A
8. Härtel, M., et al. (2023). Reducing sputter damage-induced recombination losses during deposition of the transparent front-electrode for monolithic perovskite/silicon tandem solar cells. Solar Energy Materials and Solar Cells, 252, 112180. https://doi.org/10.1016/j.solmat.2023.112180
9. Magliano, E., et al. (2023). Semitransparent perovskite solar cells with ultrathin protective buffer layers. ACS Applied Energy Materials, 6(20), 10340–10353. https://doi.org/10.1021/acsaem.3c00735

10. Smirnov, Y., Nigmetova, G., & Ng, A. (2024). Advances in top transparent electrodes by physical vapor deposition for buffer layer-free semitransparent perovskite solar cells. Solar RRL, 8, 2400354. https://doi.org/10.1002/solr.202400354
11. Fan, P., Gu, D., Liang, G.-X., Luo, J.-T., Chen, J.-L., Zheng, Z.-H., & Zhang, D.-P. (2016). High-performance perovskite $CH_3NH_3PbI_3$ thin films for solar cells prepared by single-source physical vapour deposition. Scientific Reports, 6, 29910. https://doi.org/10.1038/srep29910
12. Yang, T. C.-J., et al. (2025). Incorporating thermal co-evaporation in current-matched all-perovskite triple-junction solar cells. EES Solar. https://doi.org/10.1039/d4el00012a
13. Nikalyte Ltd. (n.d.). UHV PVD deposition system. Nikalyte. https://www.nikalyte.com/pvd-systems/uhv-pvd-deposition-system/
14. Nikalyte Ltd. (n.d.). Triple target sputter source: Tri Stellar. Nikalyte. https://www.nikalyte.com/triple-target-sputter-source-tri-stellar/