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Perovskite and Perovskite/Silicon Tandem Solar Cells: A Short Communication on Vacuum-Based Deposition and Recent Progress (2020–2026)

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Abstract- ***Perovskite solar cells (PSCs) have advanced from a 2.2% proof-of-concept in 2006 to certified single-junction efficiencies exceeding 27% and perovskite/silicon tandem efficiencies reaching 35.0% by early 2026. This short communication compiles the structural, deposition, and stability foundations established in our earlier review on vacuum and non-vacuum grown perovskite thin films, and extends it with developments reported between 2024 and 2026. Emphasis is placed on all-vacuum-deposited, solvent-free perovskite absorbers, commercial-scale tandem module shipments, lead-free absorber progress, and scalable green-synthesis routes, and their implications for vacuum-based fabrication strategies for perovskite and perovskite/silicon heterojunction devices.***

Keywords: Perovskite Solar Cells, Perovskite/Silicon Tandem, Vacuum-Based Deposition, PECVD, Stability, Lead-Free Perovskite

I. INTRODUCTION

Since Miyasaka and co-workers first demonstrated a 2.2% methylammonium lead bromide perovskite solar cell in 2006 (Kojima et al., 2006), power conversion efficiency (PCE) of single-junction perovskite solar cells (PSCs) rose past 26% within a decade and perovskite/silicon tandem devices have since surpassed the single-junction Shockley–Queisser limit of crystalline silicon. Our earlier review (Yadav and Kumar, 2024) surveyed the ABX3 perovskite structure, the roles of the electron- and hole-transport layers, and the relative merits of solution-based (spin coating, blade coating, spray coating) versus vacuum-based (thermal evaporation, RF-magnetron sputtering, chemical vapour deposition, PECVD) deposition routes, concluding that vacuum-based methods offer superior film uniformity, stoichiometric control, and scalability for perovskite and perovskite/silicon heterojunction solar cells. This short communication updates that account with the efficiency records, commercialization milestones, and vacuum-processing advances reported over the past two to three years, and adds new insights on how these developments reinforce the case for vacuum-based perovskite growth at industrial scale.

II. STRUCTURE AND DEPOSITION TECHNIQUES: A RECAP

Perovskite absorbers used in PSCs adopt the ABX3 structure, where site A is commonly methylammonium (MA+), formamidinium (FA+), or Cs+; site B is Pb2+ (or its lead-free substitutes Sn2+, Ge2+, Bi3+); and X is a halide (I−, Br−, Cl−). Devices are assembled as FTO or ITO/electron-transport layer (TiO2, SnO2, ZnO, or Y:TiO2)/perovskite absorber/hole-transport layer (Spiro-OMeTAD, PTAA, P3HT, NiO, or CuI)/metal contact, with efficiency strongly dependent on interfacial defect density and absorber crystallinity. Solution-processed one-step and two-step spin coating remain the most widely used laboratory routes, but they are intrinsically limited to small-area films with comparatively high interfacial defect densities. Vacuum-based routes – thermal co-evaporation, sequential thermal evaporation, RF-magnetron sputtering, and CVD/PECVD – deposit precursors at the atomic scale, giving denser, more compact films with better coverage over larger areas, at higher capital and running cost. Table 1 summarizes selected PCE milestones from the earliest PSC report through the present tandem world record, situating the new results discussed in Section 3 within the decade-scale trend already documented in our review.

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Table 1. Selected PCE milestones for perovskite and perovskite/silicon tandem solar cells (2006–2026).

Author & Year	Device / Milestone	η (%)	Reference
Kojima et al. (2006)	CH3NH3PbBr3/TiO2 (first PSC)	2.2	Kojima et al., 2006
Burschka et al. (2013)	Glass/FTO/TiO2/CH3NH3PbX3/HTM/Au	15	Burschka et al., 2013
Min et al. (2021)	Metal oxide ETL/FASnClx/Organic HTL	25.8	Min et al., 2021
NREL (2025)	Certified single-junction PSC (small-area)	27.3	NREL, 2025
Al-Ashouri et al. (2020)	Monolithic perovskite/Si tandem	29.15	Al-Ashouri et al., 2020
Kim et al. (2021)	Bifacial 4-T perovskite/Si tandem	30.09	Kim et al., 2021
LONGi (2023)	2-T perovskite/Si tandem	33.9	Longi claims 33.9%
JinkoSolar (2024–25)	2-T perovskite/Si tandem, n-type wafer	33.84	Ceramic Soc., 2025
LONGi (2025)	2-T perovskite/Si tandem	34.85	Fluxim, 2026
LONGi (2026, NREL-certified)	2-T perovskite/Si tandem – present world record	35.0	NREL, 2026; Wikipedia, 2026

III. RECENT PROGRESS (2024–2026)

3.1 Efficiency records

The single-junction PSC record, certified by NREL, now stands at 27.3% (NREL, 2025), an improvement of roughly 1.5 percentage points over the 25.8% figure available at the time of our review. More strikingly, perovskite/silicon tandem cells have progressed from the 33.9% record reported by LONGi Green Energy in late 2023 to successive certified milestones of 34.6% and 34.85% through 2024–2025, and finally to a 35.0% NREL-certified world record by LONGi in February 2026 – the highest efficiency reported for any two-terminal tandem photovoltaic technology to date. JinkoSolar independently reported 33.84% on an n-type wafer platform, and an early-2026 report in Nature described a certified 33.6% flexible perovskite/silicon tandem cell, indicating that the tandem approach is no longer confined to rigid, small-area laboratory devices.

3.2 Commercial and module-scale progress

Translating cell-level gains to modules has accelerated. Oxford PV shipped its first commercial 72-cell tandem modules (24.5% efficiency) to U.S. utility customers in September 2024 and has since reported 26.8% on large-area commercial-size substrates, while operating a dedicated production line in Brandenburg, Germany. Hanwha Qcells reported 28.6% efficiency on a full mass-producible M10-format cell (330.56 cm²) in December 2024. On the all-perovskite (non-tandem) module front, UtmoLight reported an 18.1% efficiency on a 0.72 m² module from a 150 MW pilot line in March 2025, and a separate 10 cm × 10 cm module retained 94% of its initial efficiency after 1000 hours of light soaking at 65% relative humidity, evidencing incremental but still-partial progress on the stability front. Table 2 lists these module- and commercial-scale developments alongside the first certified all-vacuum-deposited device (Section 3.3).

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Table 2. Module-scale, commercial, and vacuum-processing milestones reported in 2024–2026.

Group / Year	Device / Milestone	η (%)	Reference
Hanwha Qcells (Dec 2024)	Full M10-size (330.56 cm²) tandem cell	28.6	Ceramic Soc., 2025
Oxford PV (Sep 2024)	First commercial 72-cell tandem module shipment	24.5	SurgePV, 2026
Oxford PV (2026)	Large-area commercial tandem module	26.8	SurgePV, 2026
UtmoLight (Mar 2025)	0.72 m² perovskite module, 150 MW pilot line	18.1	Ceramic Soc., 2025
Wang, Li, Yu et al. (2026)	Certified flexible perovskite/Si tandem	33.6	Green Fuel J., 2026
Shen et al. (2026)	First all-vacuum-deposited wide-bandgap PSC (0.25 cm², MPP-tracked)	18.35	Nat. Mater., 2026

3.3 All-vacuum-deposited perovskites: a direct extension of our review

A development of particular relevance to the vacuum-processing focus of our earlier review is the first certified all-vacuum-deposited, solvent-free perovskite solar cell, reported by Shen et al. (2026) in Nature Materials. Using a multi-source co-evaporation process that incorporates PbCl2 as a crystallization-directing additive, the authors obtained a highly ordered, wide-bandgap (1.67 eV) perovskite film with grains preferentially aligned in the (100) 'face-up' orientation – a crystal-facet control strategy not accessible by solution processing. The resulting device reached 19.3% efficiency in the laboratory and a certified, maximum-power-point-tracked 18.35% on a 0.25 cm2 cell, with markedly improved resistance to light- and heat-driven degradation relative to solution-processed analogues of comparable bandgap. This result substantiates the central argument of our 2024 review – that vacuum-based deposition, despite its higher capital cost, offers a route to superior film crystallinity, stoichiometric control, and stability – and extends it from the two-step MAPbI3 evaporation and PECVD routes we previously discussed to fully integrated, solvent-free device fabrication.

3.4 Lead-free absorbers and stability

Stability and toxicity, identified as the two principal barriers to PSC commercialization in our review, remain active research fronts. A 2026 review in Advanced Sustainable Systems (Barua et al., 2026) notes that tin-based PSCs have improved substantially between 2014 and 2025, while germanium-, bismuth-, and antimony-based absorbers, though still trailing lead-based devices in PCE, exhibit comparatively better intrinsic stability; alloying strategies (partial Ge or Bi substitution, halide mixing) and ALD-deposited Al2O3 or polymer encapsulation are highlighted as the principal levers for narrowing this gap. This is consistent with, and extends, the doping and stabilization strategies (Sn incorporation, Rb+ and Cs+ substitution at the A-site, C60 additives) surveyed in our original article.

3.5 Scalable and green fabrication routes

A 2024–2025 survey in Nano-Micro Letters highlights several manufacturing-oriented advances that complement the deposition techniques discussed in our review: green-solvent formulations and ambient-air fabrication protocols aimed at reducing the use of hazardous solvents such as DMF; kilogram-scale aqueous-phase synthesis of formamidinium lead iodide microcrystals at 99.994% purity; vacuum flash evaporation for rapid, large-area film crystallization; and machine-learning-assisted composition and process optimization. Together with blade coating, slot-die coating, and roll-to-roll processing, these routes are identified as the principal strategies for closing the persistent efficiency gap between small-area laboratory cells and full-size perovskite modules.

IV. OUTLOOK AND CONCLUSION

The developments compiled here confirm and sharpen the trajectory outlined in our original review: perovskite photovoltaics have moved from a laboratory curiosity to a technology approaching commercial deployment, with certified tandem efficiencies (35.0%) now substantially exceeding the practical ceiling of single-junction silicon, and with the first commercial tandem module shipments already underway. At the same time, the emergence of a fully vacuum-deposited, solvent-free device with improved crystallinity and stability directly validates the vacuum-based deposition strategies – thermal evaporation, sputtering, CVD, and PECVD – emphasized throughout our earlier work, including our own PECVD-grown MAPbI3 and doped perovskite/silicon heterojunction studies. Continued progress on lead-free absorbers, encapsulation, and green, scalable manufacturing will determine how quickly these laboratory and pilot-line gains translate into bankable, field-durable perovskite and perovskite/silicon tandem modules.

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