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Perovskite nanomaterials and nanostructures manufacturing: from atomic to wafer scale engineering

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Metal halide perovskites stand at the nexus of materials innovation, nanoscale engineering, and real-world device integration. Their journey from laboratory curiosities to contenders for commercial photovoltaics, radiation detectors, and photocatalytic systems has been propelled not only by exceptional optoelectronic properties—but decisively, by *how* they are fabricated, structured, and interfaced. This Special Issue of *Light: Advanced Manufacturing*, titled "*Perovskite Nanomaterials and Nanostructures Fabrication for Photonics and Optoelectronics*", showcases a new generation of research where synthesis, nanostructuring, and interfacial control converge to solve long-standing challenges: instability in operational environments, poor reproducibility, scalability bottlenecks, and performance ceilings.

The eight contributions featured here, which were selected from a competitive pool of submissions, illustrate a field in transition: from proof-of-concept demonstrations toward *manufacturable*, *multifunctional*, and *mission-critical* systems. Notably, the ordering of papers in this issue traces a deliberate arc, from *molecular-level synthesis* and *colloidal control*, through *nanoscale patterning* and *heterostructure design*, to *device-level integration* and *extreme-environment resilience*, reflecting the hierarchical complexity of modern perovskite engineering.

It begins at the nanoscale synthesis frontier, where Paper 1 tackles perhaps the most persistent limitation of perovskites: instability in aqueous media. By developing a *one-pot hot-injection route* to fabricate *water-stable $CsPbBr_3@TiO_2$ core-shell nanocrystals* (further augmented with plasmonic Au nanoparticles) the authors unlock efficient, selective solar-driven CO_2 reduction in water, achieving up to 70% Faradaic efficiency for propene (C_3H_6). This work powerfully demonstrates that *nanoscale encapsulation and plasmonic coupling* can jointly overcome thermodynamic and kinetic barriers, opening a pathway toward solar fuels and green chemistry.

Paper 2 sharpens the focus on reproducibility and defect control in colloidal quantum dots, a longstanding pain point. Through meticulous precursor engineering (acetate + 2-hexyldecanoic acid), the authors boost cesium precursor purity from 70% to > 98%, achieving near-unity PLQY (99%), narrow emission (22 nm), and (critically) a 70% reduction in ASE threshold. This level of batch-to-batch consistency, rarely reported in perovskite QD literature, signals a maturing synthesis protocol ready for transfer to pilot-scale production.

Papers 3 and 4 are based on *top-down and bottom-up patterning*, where form meets function. Paper 3 introduces a non-invasive *substrate-guided nanostructuring* approach: depositing perovskite films atop laser-induced periodic surface structures (LIPSS) in TiO_2. Without ablating or damaging the perovskite, this method yields structural colouration, luminescence anisotropy, and enhanced charge extraction—at a writing speed of 2.25 cm^2/min, which is

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promising for roll-to-roll adoption. Complementing this, Paper 4 presents a universal dry lift-off micro-patterning technique achieving ~1 μm resolution across 100 mm wafers and demonstrates direct integration of perovskite and CdSe QD arrays onto GaN LED chips for colour—conversion microdisplays. Together, these works bridge nanofabrication and device integration, thus addressing a critical gap in scalable optoelectronic manufacturing.

The middle of the issue turns to *interface and bulk engineering*. Paper 5 leverages the ferroelectric polymer P(VDF-TrFE) to *pin the Fermi level* and suppress interfacial trap states in photodiodes. The result: detectivity surpassing 10^{12} Jones, 100 dB linear dynamic range, and improved thermal stability—advancing perovskite photodetectors toward parity with established technologies. Crucially, the dielectric integration preserves morphology, proving that *electronic*—not structural—tuning can yield transformative gains.

Papers 6 and 7 return to the *wide-bandgap perovskite* $Cs_{0.17}FA_{0.83}PbI_{1.8}Br_{1.2}$, a workhorse for perovskite/Si tandems. Paper 6 applies bi-solvent engineering to achieve not only lab-scale efficiency gains but, remarkably, a 10% efficient 25 cm^2 mini-module using acetonitrile-based processing. This is a significant step toward manufacturability. Paper 7 then subjects the *same composition* to γ-ray irradiation, uncovering a surprising defect-passivation mechanism at doses $\leq$ 10 kGy, enabling radiation-hardened solar cells. These complementary studies underscore that *processing* and *environmental response* must be co-optimized, especially for space or nuclear applications.

Finally, Paper 8 closes the issue on a forward-looking, application-driven note: a lead-free, flexible X-ray scintillator based on a novel 0D cuprous halide, $(MTP)_2Cu_4I_6$. With near-unity PLQY (99.9%), negligible self-absorption, sub-μs response, and 10.2 lp·mm^{-1} resolution in PDMS films, this material challenges the dominance of toxic or brittle alternatives in medical and security imaging. Its success exemplifies how *perovskite-inspired* (though not perovskite-structured) materials can fulfill real-world safety and performance requirements—expanding the field's impact beyond classical device architectures.

Collectively, these papers embody a maturing discipline. Where early perovskite research emphasized composition space and record efficiencies, today's frontier lies in fabrication control: across length scales, from atomic ligands to wafer-scale patterning; across environments, from ambient air to ionizing radiation; and across applications, from microdisplays to carbon-neutral fuel synthesis.

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Data availability

All data are available from the corresponding authors upon reasonable request.

Conflict of interest

Nikolay Petrov is a member of the editorial board of the journal, and no other author has reported any competing interests.

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