International Journal on Recent and Innovation Trends in Computing and Communication
ISSN: 2321-8169 Volume: 10 Issue: 6
Article Received: *25 April 2022* ***Revised:*** *12 May 2022* ***Accepted:*** *30 June 2022*

Design and Characterization of Nanostructured Materials for High-Efficiency Photovoltaic and Optoelectronic Applications Synthesis Strategies, Structure-Property Relationships, and Device Integration

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Abstract

Nanostructuring has become one of the most powerful design levers available for improving the efficiency, stability, and functionality of photovoltaic (PV) and optoelectronic devices. By confining charge carriers to length scales comparable to or smaller than their de Broglie wavelength, and by sculpting material morphology at the sub-wavelength scale, nanostructured absorbers, transport layers, and light-management architectures can address several loss mechanisms simultaneously: parasitic reflection, insufficient absorption in thin films, non-radiative recombination at interfaces, and poor spectral matching to the solar spectrum. This paper reviews the principal classes of nanostructured materials used in modern photovoltaics and optoelectronics zero-dimensional quantum dots, one-dimensional nanowires and nanorods, two-dimensional nanosheets, and three-dimensional nanotextured and plasmonic architectures together with the synthesis routes, structural and optical characterization methods, and device integration strategies associated with each. Particular attention is given to halide perovskite quantum dots and nanocrystals, silicon and III–V nanowire arrays for light trapping and tandem integration, and plasmonic nanostructures for near-field and far-field light management. Representative case studies are discussed, including ligand- and interface-engineered perovskite quantum-dot solar cells achieving certified efficiencies above 24%, embedded silicon-nanowire interlayers proposed for perovskite/silicon tandem cells, and nanocone and nanopillar antireflection textures for ultrathin crystalline-silicon absorbers. The review concludes with a discussion of persistent challenges in stability, scalable and reproducible synthesis, and toxicity, and outlines future directions including lead-free nanocrystal absorbers, machine-learning-guided synthesis optimization, and integration with tandem and multi-junction architectures.

Keywords: *nanostructured materials; photovoltaics; optoelectronics; quantum dots; nanowires; light trapping; perovskite solar cells; plasmonics; quantum confinement.*

1. Introduction

Photovoltaic and optoelectronic devices convert light into electrical energy, or electrical signals into light, through the generation, separation, transport, and collection or recombination of charge carriers in semiconducting materials. The performance of these devices is fundamentally constrained by the interplay of optical absorption, carrier transport, and interfacial recombination, and by the Shockley Queisser detailed-balance limit that bounds the efficiency achievable by any single-junction absorber under unconcentrated sunlight [1], [2]. Conventional planar, bulk, or thin-film architectures face a persistent design tension: absorber layers must be thick enough to absorb a useful fraction of incident light, yet thin enough that photogenerated carriers can be collected before recombining, a tension that is especially acute for materials with modest absorption coefficients or short minority-carrier diffusion lengths.

Nanostructuring offers a route to decouple these competing requirements. By patterning absorber or light-management layers at length scales comparable to the wavelength of visible and near-infrared light, nanostructures such as nanowires, nanocones, and

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nanopillars can act as effective antireflection and light-trapping media, increasing the optical path length within a physically thin absorber without a corresponding increase in the carrier collection distance [3]–[6]. At even smaller length scales, quantum-confined nanocrystals and quantum dots exhibit a size-tunable bandgap governed by quantum confinement, enabling spectral matching to specific device requirements and access to physical effects such as multiple exciton generation that are absent in bulk semiconductors and that offer a potential route to exceeding the single-junction Shockley–Queisser limit [7], [8].

This review surveys the design, synthesis, and characterization of nanostructured materials for photovoltaic and optoelectronic applications, with an emphasis on developments most relevant to current high-efficiency device architectures: halide perovskite quantum dots and nanocrystals, silicon and III–V semiconductor nanowires, plasmonic metal nanostructures, and nanotextured light-trapping surfaces for both single-junction and tandem cells. Section 2 introduces the fundamental physical principles that make Nanostructuring advantageous for photovoltaics. Section 3 surveys the principal morphological classes of nanostructured materials and their associated synthesis routes. Section 4 discusses optical and electronic design principles, including quantum confinement and band alignment. Section 5 reviews structural, optical, and electrical characterization methods. Section 6 examines device integration strategies and application domains. Section 7 presents case studies drawn from the recent literature. Section 8 discusses stability, scalability, and toxicity challenges, and Sections 9 and 10 present future directions and conclusions.

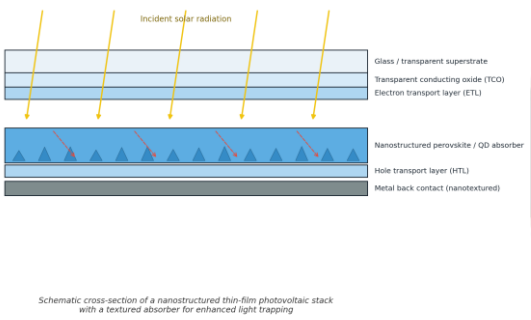

Figure 1. Schematic cross-section of a representative nanostructured thin-film photovoltaic device stack, illustrating a nanotextured absorber layer for enhanced light trapping between charge-transport layers.

2. Fundamentals of Nanostructured Photovoltaic Materials

2.1 The Shockley–Queisser Limit and Motivations for Nanostructuring

The Shockley–Queisser detailed-balance analysis establishes a theoretical maximum power-conversion efficiency (PCE) for a single-junction solar cell as a function of absorber bandgap, close to 33.7% for an ideal absorber under standard AM1.5G illumination, with practical crystalline-silicon devices now approaching the corresponding practical limit for that bandgap [1], [2], [9], [10]. Because this limit is fundamentally set by unavoidable thermalization and transmission losses for a single absorber bandgap, further efficiency gains beyond the single-junction limit require either multi-junction (tandem) architectures that partition the solar spectrum across absorbers of different bandgap, or mechanisms such as multiple exciton generation in strongly confined nanocrystals that alter the basic assumptions of the detailed-balance derivation [8], [11]. Nanostructuring is central to both strategies: it enables efficient light management and carrier collection in the thin, optically and electronically distinct layers required for tandem integration, and it provides the quantum-confinement-tunable bandgaps needed to spectrally match each subcell to its portion of the solar spectrum [5], [6], [12].

2.2 Quantum Confinement and Size-Tunable Bandgap

When the physical dimension of a semiconductor nanocrystal approaches or falls below the material's exciton Bohr radius, the energy levels of confined charge carriers become discretized, and the effective optical bandgap increases with decreasing particle size, a phenomenon known as quantum confinement. This effect is exploited extensively in colloidal quantum-dot photovoltaics, where the emission and absorption onset of nanocrystals such as lead halide perovskite quantum dots (PQDs) can be tuned across the visible and near-infrared spectrum simply by controlling nanocrystal size and halide composition during synthesis, without requiring a change in the underlying crystal structure [7], [13], [14].

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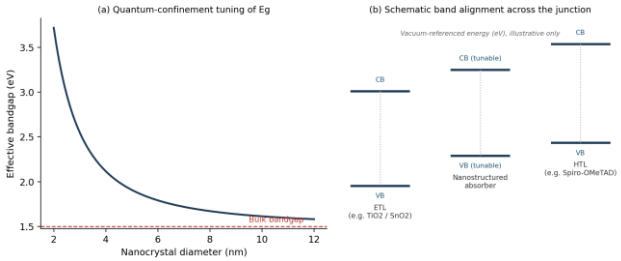

Figure 2. (a) Schematic illustration of quantum-confinement-driven bandgap widening as nanocrystal diameter decreases below the bulk exciton Bohr radius. (b) Schematic conduction-band (CB) and valence-band (VB) alignment across a nanostructured absorber and its adjacent electron- and hole-transport layers; energies are illustrative and not to scale for any specific material system.

2.3 Light Trapping and Antireflection

A complementary rationale for nanostructuring, distinct from quantum confinement, applies at the device and film level rather than the individual-particle level: sub-wavelength surface texturing can suppress front-surface reflection and increase the effective optical path length of light within an absorber layer, both of which increase the fraction of incident photons absorbed for a given physical film thickness. Vertically aligned silicon nanowire, nanocone, and nanopillar arrays have long been recognized as effective broadband antireflection and light-trapping structures for crystalline and thin-film silicon photovoltaics, with measured reflectance reduced dramatically relative to planar silicon across the visible and near-infrared range [3], [4], [15], [16]. Plasmonic metal nanostructures provide a related but distinct mechanism, using localized surface plasmon resonances to concentrate near-field electromagnetic energy or scatter light into guided modes within the absorber, and have been used both as front-surface scattering elements and as nanopatterned back reflectors in silicon-based multi-junction cells [17], [18].

3. Classes of Nanostructured Materials and Synthesis Strategies

Nanostructured photovoltaic materials are conventionally organized by dimensionality, summarized schematically in Figure 3, with each morphological class associated with distinct synthesis routes, characteristic optical and electronic behavior, and typical device roles.

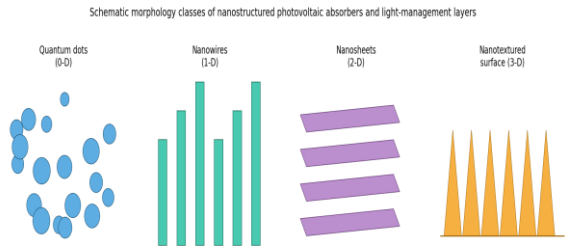

Figure 3. Schematic morphology classes of nanostructured photovoltaic materials: zero-dimensional quantum dots, one-dimensional nanowires, two-dimensional nanosheets, and three-dimensional nanotextured surfaces.

3.1 Zero-Dimensional Nanostructures: Quantum Dots and Nanocrystals

Colloidal quantum dots, including lead halide perovskite quantum dots (e.g., CsPbX3, X = Cl, Br, I) and chalcogenide quantum dots (e.g., PbS, PbSe, CuGaS2), are typically synthesized via hot-injection or ligand-assisted reprecipitation methods that afford fine control over particle size, shape, and surface ligand chemistry [13], [19], [20]. Surface ligands play a dual role: they provide colloidal stability and passivate surface trap states that would otherwise promote non-radiative recombination, but they can also impede interparticle or particle-to-electrode charge transport if not carefully engineered, motivating extensive research into ligand-exchange and ligand-shortening post-treatments for quantum-dot solar-cell fabrication [13], [21]. Carbon quantum dots represent a related, more recently developed class of nanostructured material valued for low toxicity and environmentally benign synthesis, and are increasingly explored as auxiliary layers in quantum-dot and perovskite photovoltaics [22].

3.2 One-Dimensional Nanostructures: Nanowires and Nanorods

Semiconductor nanowires including silicon, III–V compound (e.g., GaAs, InP), and metal-oxide nanowires are typically grown via vapor–liquid–solid (VLS) chemical vapor deposition, metal-assisted chemical etching (MACE), or template-assisted electrodeposition. Silicon nanowire arrays fabricated by MACE, in particular, are widely used because the process is low-cost, scalable, and compatible with existing silicon-wafer processing infrastructure, and because the resulting arrays exhibit excellent broadband antireflection properties [4], [15], [23]. A persistent challenge for etched nanowire arrays is the high density of surface states introduced by the large surface-to-volume ratio,

which increases non-radiative surface recombination; passivation strategies including thin dielectric (e.g., Al2O3) coatings and surface-modifying chemical treatments have been shown to substantially improve device performance by suppressing this loss channel [23], [24].

3.3 Two-Dimensional Nanostructures: Nanosheets and Layered Materials

Two-dimensional nanosheets, including exfoliated transition-metal dichalcogenides and layered halide perovskites, offer high surface area, tunable electronic structure through layer-number control, and, in some cases, intrinsic environmental stability advantages over their three-dimensional bulk counterparts. In photovoltaic applications, 2-D nanosheets are frequently employed as interfacial passivation or charge-selective layers rather than as the primary absorber, capitalizing on their high in-plane carrier mobility and chemically tunable surface termination to reduce interfacial recombination at absorber/transport-layer junctions.

3.4 Three-Dimensional Nanotextured and Plasmonic Architectures

Three-dimensional nanotextured surfaces nanocone, nanopillar, and nanohole arrays fabricated by nanoimprint lithography, interference lithography, or self-assembled etch masks are used primarily for light management rather than as active absorbers in their own right. Comparative studies of nanowire, nanocone, and nanopillar silicon architectures, in some cases combined with silicon-nitride antireflection coatings, have demonstrated that light-trapping performance depends sensitively on nanostructure geometry, periodicity, and aspect ratio, motivating simulation-guided optimization of structure parameters prior to fabrication [16], [25], [26]. Plasmonic back reflectors, formed from periodic or quasi-periodic silver or gold nanostructures, provide a complementary strategy for enhancing light trapping in the near-infrared, where absorption in thin silicon layers is otherwise weak [17], [18].

4. Optical and Electronic Design Principles

4.1 Band-Alignment Engineering

Efficient charge extraction in a nanostructured device requires favorable energy alignment between the absorber and its adjacent electron- and hole-transport layers, so that photogenerated electrons and holes are preferentially extracted toward their respective contacts while back-transfer and interfacial recombination are suppressed (Figure 2b). In nanocrystal-based absorbers, this alignment can be tuned not only through choice of transport-layer material but also through the size- and composition-dependent band edges of the nanocrystals themselves, providing an additional design parameter unavailable in bulk-film absorbers [7], [14]. Charge-separating heterostructures formed by layer-by-layer deposition of compositionally distinct perovskite quantum dots have been shown to improve photocarrier harvesting relative to compositionally uniform quantum-dot films, by creating a graded internal energy landscape that drives directional charge transport [27].

4.2 Multiple Exciton Generation and Beyond-Shockley–Queisser Strategies

In sufficiently strongly confined nanocrystals, absorption of a single high-energy photon can generate more than one electron–hole pair through multiple exciton generation (MEG), a process negligible in bulk semiconductors but enhanced by the modified carrier relaxation pathways available in quantum-confined systems. Realizing a net efficiency benefit from MEG in a working photovoltaic device requires that the additional carriers be extracted before Auger recombination returns the system to a single exciton, and reviews of perovskite quantum-dot photovoltaics identify MEG-based approaches as a promising, if not yet fully realized, route to exceed the conventional single-junction efficiency limit [7].

4.3 Defect Tolerance and Surface Passivation

Halide perovskites, in both bulk-film and nanocrystal form, are frequently noted for a degree of intrinsic defect tolerance not shared by conventional covalent semiconductors, in which many common point defects introduce shallow rather than deep trap states and therefore contribute comparatively weakly to non-radiative recombination. This property does not eliminate the importance of surface and interface passivation, however, particularly for nanocrystals with very high surface-to-volume ratios: recent work has demonstrated that combining ligand-driven bandgap tuning with covalent surface-locking strategies, or fluorination-based interface treatments, can substantially extend operational and thermal stability while maintaining high certified efficiency, and that incorporating quantum dots into nanostructured carbon interlayers can provide a physical barrier against moisture and oxygen ingress [13], [21].

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5. Characterization Methods

Reliable structure–property–performance correlations for nanostructured photovoltaic materials require characterization spanning structural, optical, and electrical/device domains, summarized in the representative workflow shown in Figure 4.

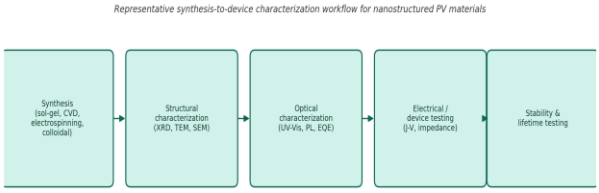

Figure 4. Representative synthesis-to-device characterization workflow for nanostructured photovoltaic materials, spanning structural, optical, and electrical/device-level analysis through to long-term stability testing.

5.1 Structural Characterization

X-ray diffraction (XRD) is used to confirm crystal phase and estimate crystallite size via peak broadening analysis, while transmission electron microscopy (TEM), including high-resolution TEM, provides direct imaging of nanocrystal size, shape, and lattice structure and can reveal atomic-scale defects such as twin boundaries that influence photovoltaic performance and stability [28]. Scanning electron microscopy (SEM) is the standard tool for characterizing the geometry, periodicity, and aspect ratio of nanowire, nanocone, and nanopillar arrays fabricated for light management.

5.2 Optical Characterization

UV–visible absorption and photoluminescence (PL) spectroscopy are used to determine absorption onset, quantify quantum-confinement-driven bandgap shifts, and assess radiative recombination efficiency via photoluminescence quantum yield; statistical analysis of single-nanocrystal photoluminescence fluctuations has additionally been used to probe blinking and intermittency phenomena relevant to nanocrystal optoelectronic quality at the single-particle level [29]. External quantum efficiency (EQE) measurements, which quantify the fraction of incident photons at each wavelength converted to collected charge carriers, provide a device-level probe of combined optical absorption and carrier-collection efficiency, and are essential for validating light-trapping enhancements predicted by optical simulation.

5.3 Electrical and Device-Level Characterization

Current density–voltage (J–V) measurements under standard simulated AM1.5G illumination yield the primary photovoltaic figures of merit short-circuit current density (Jsc), open-circuit voltage (Voc), fill factor (FF), and power-conversion efficiency (PCE) while impedance spectroscopy and related transient techniques probe interfacial recombination dynamics and charge-transport resistances not directly accessible from steady-state J–V curves alone. Long-term operational and thermal stability testing, typically reported as retained PCE after prolonged continuous illumination or elevated-temperature storage, has become an increasingly standard component of device characterization given the well-documented stability challenges of halide perovskite materials [13], [21].

Table 1. Summary of principal nanostructured material classes used in photovoltaic and optoelectronic devices.

Nanostructure Class	Typical Synthesis	Primary Device Role	Key Reference(s)
Perovskite / chalcogenide quantum dots	Hot injection; ligand-assisted reprecipitation	Tunable-bandgap absorber; interfacial passivation	[7], [13], [19]–[21]
Silicon / III–V nanowires	VLS-CVD; metal-assisted chemical etching	Light trapping; antireflection; tandem interlayer	[3]–[6], [15], [16], [23]
2-D nanosheets / layered materials	Liquid-phase exfoliation; solution growth	Interfacial / charge-selective passivation layer	(general literature)

Nanotextured surfaces & plasmonic reflectors	Nanoimprint / interference lithography; self-assembled etch masks	Broadband light trapping; back-reflection	[16]–[18], [25], [26]

6. Device Integration and Applications

6.1 Single-Junction Quantum-Dot and Perovskite Solar Cells

Perovskite quantum-dot solar cells (PQDSCs) have advanced rapidly, with reported single-junction certified efficiencies rising from below 10% to beyond 24% within a relatively short development period, driven by improvements in surface ligand chemistry, compositional control, and interfacial engineering [13], [20], [21]. Reported strategies combining ligand-driven bandgap tuning with covalent interface locking have demonstrated devices retaining roughly 90% of initial performance after over a thousand hours of continuous illumination, alongside thermal stability sufficient to retain the majority of performance after extended storage and elevated-temperature operation, addressing what has historically been one of the central barriers to PQDSC commercialization [13].

6.2 Tandem and Multi-Junction Integration

Nanostructured interlayers and light-management architectures play an increasingly central role in tandem photovoltaic design, where efficient optical coupling between subcells of different bandgap is essential to realizing the theoretical efficiency advantage of multi-junction architectures over single-junction devices. Embedding vertically aligned silicon nanowires between the perovskite and silicon subcells of a two-terminal tandem cell has been proposed as a strategy to reduce interfacial reflection losses and couple light into guided resonant modes, with simulation-based studies reporting substantial enhancement in short-circuit current density and overall power-conversion efficiency relative to conventional planar-interface tandem architectures [6]. Antireflective nanotexturing at the front surface of monolithic perovskite/silicon tandem cells has similarly been shown, through numerical optical optimization, to reduce reflection losses across the combined absorption range of both subcells [5].

6.3 Plasmonically Enhanced Thin-Film Devices

For thin-film silicon and related absorbers where near-infrared absorption is intrinsically weak due to silicon's indirect bandgap, plasmonic nanostructured back reflectors combining engineered near-field and far-field light scattering have been used to extend the effective optical path length within the absorber without increasing its physical thickness, with reported designs combining periodic silver nanostructures and dielectric antireflection coatings to enhance broadband absorption in multi-junction thin-film architectures [17], [18].

7. Case Studies

7.1 Ligand- and Interface-Engineered Perovskite Quantum-Dot Solar Cells

A representative case study reports a dual-function strategy combining ligand-driven bandgap tuning with covalent surface-locking chemistry applied to lead halide perovskite quantum dots, yielding devices that retained approximately 89% of initial efficiency after 500 hours of continuous illumination, a 41% improvement in retained performance relative to unmodified quantum-dot devices over the same interval [13]. A related fluorination-based interface-locking treatment reported in the same review area achieved a certified power-conversion efficiency of 24.6%, with over 90% of initial performance retained after 1,150 hours of continuous illumination and roughly 85% retained after 14,400 hours of ambient storage, together with stable operation after 200 hours at 125°C, illustrating the combined efficiency and stability gains achievable through coordinated ligand and interface engineering [13].

7.2 Embedded Silicon-Nanowire Interlayers for Perovskite/Silicon Tandem Cells

A simulation study proposed a two-terminal perovskite/silicon tandem architecture incorporating vertically aligned silicon nanowires embedded between the two subcells, grown directly on the silicon bottom cell [6]. Finite-difference time-domain optical simulation showed that the sub-wavelength nanowires supported guided resonant modes that coupled incident light more effectively between subcells and reduced interlayer reflection losses across the combined absorption spectrum; corresponding electrical simulation, using carrier-generation profiles derived from the optical results, projected a 22.6% enhancement

in short-circuit current density and an increase in power-conversion efficiency from 26.98% to 32.11% relative to a conventional planar-interface tandem of otherwise identical composition [6]. While based on simulation rather than fabricated devices, the study provides a concrete theoretical framework and target performance metrics intended to guide subsequent experimental realization.

7.3 Nanocone and Nanopillar Antireflection Textures for Ultrathin Silicon Absorbers

A further case study compared silicon nanowire, nanocone, and nanopillar architectures, fabricated via silver-assisted electroless etching and inductively coupled plasma etching with extreme-ultraviolet lithography, evaluating optical absorption through simulation and validating power-conversion-efficiency improvements experimentally via current density–voltage characterization with and without a silicon-nitride antireflection overlayer [16]. The comparative approach illustrated that light-trapping performance depends sensitively on nanostructure geometry and periodicity, and that combining geometric nanotexturing with a conventional dielectric antireflection coating provided a larger net PCE improvement than either strategy alone.

8. Stability, Scalability, and Toxicity Challenges

8.1 Operational and Environmental Stability

Halide perovskite nanocrystals, despite substantial recent progress, remain more susceptible than many conventional inorganic semiconductors to degradation from moisture, oxygen, thermal stress, and ion migration, with halide ion migration in particular identified as a critical degradation pathway; strategies such as extending diffusion path length and physically blocking low-energy ion-migration channels through incorporation into nanostructured carbon interlayers have been shown to slow, though not entirely eliminate, this degradation mode [13]. Because operational stability under realistic illumination and temperature cycling remains one of the most commonly cited barriers to commercialization of nanocrystal-based photovoltaics, standardized and sufficiently long-duration stability testing protocols are an important complement to efficiency reporting.

8.2 Scalable and Reproducible Synthesis

Many of the highest-efficiency results reported for nanostructured photovoltaic materials, particularly colloidal quantum dots and etched nanowire arrays, are obtained using batch synthesis or fabrication methods whose reproducibility and cost-effectiveness at industrial scale are not yet fully established. Metal-assisted chemical etching of silicon nanowires is frequently highlighted as comparatively scalable because it is compatible with existing wafer-processing infrastructure, but surface-defect passivation and uniformity across large-area substrates remain active areas of process development [4], [23].

8.3 Toxicity and Environmentally Benign Alternatives

The most efficient halide perovskite and chalcogenide nanocrystal systems reported to date generally contain lead or other elements of environmental and regulatory concern, motivating continued research into lead-free or reduced-toxicity nanocrystal absorbers, such as tin-based or double-perovskite compositions, and into environmentally benign nanomaterials such as carbon quantum dots, which are explicitly noted in the literature for low toxicity, biosafety, and environmentally friendly synthesis routes, albeit generally at lower photovoltaic efficiency than their lead-based counterparts at present [22].

9. Future Directions

- Lead-free and reduced-toxicity nanocrystal absorbers: continued development of tin-based, double-perovskite, and chalcogenide nanocrystal compositions that narrow the efficiency gap with lead halide perovskite quantum dots while addressing toxicity and regulatory concerns [22].
- Machine-learning-guided synthesis and structure optimization: coupling high-throughput synthesis with automated structural and optical characterization and machine-learning-based optimization to accelerate discovery of ligand chemistries, compositions, and nanostructure geometries with improved efficiency and stability.
- Advanced tandem and multi-junction integration: further development of nanostructured interlayers, such as embedded nanowire arrays and nanotextured recombination junctions, to minimize optical and electrical losses at subcell interfaces in perovskite/silicon and other tandem architectures [5], [6].
- Standardized long-duration stability protocols: broader adoption of extended illumination, thermal

cycling, and environmental exposure testing, reported using consistent metrics, to enable direct comparison of stability claims across the rapidly growing nanostructured-photovoltaics literature [13], [21].

- Beyond-Shockley–Queisser mechanisms: further experimental realization of multiple-exciton-generation and hot-carrier extraction strategies in strongly confined nanocrystal absorbers, moving beyond proof-of-concept demonstrations toward integration in efficient working devices [7], [8].
- Multifunctional and flexible optoelectronic integration: extension of nanostructured photovoltaic materials and light-management architectures toward flexible, semi-transparent, and multifunctional optoelectronic devices, including photodetectors and light-emitting applications that share common nanostructure design principles with photovoltaic absorbers.

10. Conclusion

Nanostructuring has become an indispensable design strategy across the photovoltaic and optoelectronic device landscape, addressing optical, electronic, and interfacial loss mechanisms that are difficult to mitigate through bulk-material or planar-architecture approaches alone. Zero-dimensional quantum dots provide size- and composition-tunable bandgaps and access to physical mechanisms, such as multiple exciton generation, unavailable in bulk semiconductors; one-dimensional nanowire and nanocone arrays deliver broadband antireflection and light trapping while decoupling absorption length from carrier-collection distance; two-dimensional nanosheets offer tunable interfacial passivation layers; and three-dimensional nanotextured and plasmonic architectures extend effective optical path length in physically thin absorbers. Recent case studies demonstrate that coordinated advances in ligand chemistry, interface engineering, and nanostructure geometry can simultaneously improve efficiency and operational stability, with certified perovskite quantum-dot solar-cell efficiencies now exceeding 24% and simulation-guided nanowire-interlayer tandem architectures projecting efficiencies above 32%. Nonetheless, substantial challenges around long-term stability, scalable and reproducible synthesis, and the toxicity of lead-based absorber materials remain open, and addressing them through lead-free material development, standardized stability testing, and increasingly data-driven synthesis optimization represents a critical direction for the continued advancement of nanostructured photovoltaic and optoelectronic technology.

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