

Review Article

Advances in Energy-Efficient Nanostructured Solar Cells: An Interdisciplinary Review of Quantum Materials, Nanotechnology, and Power Electronics Perspectives.

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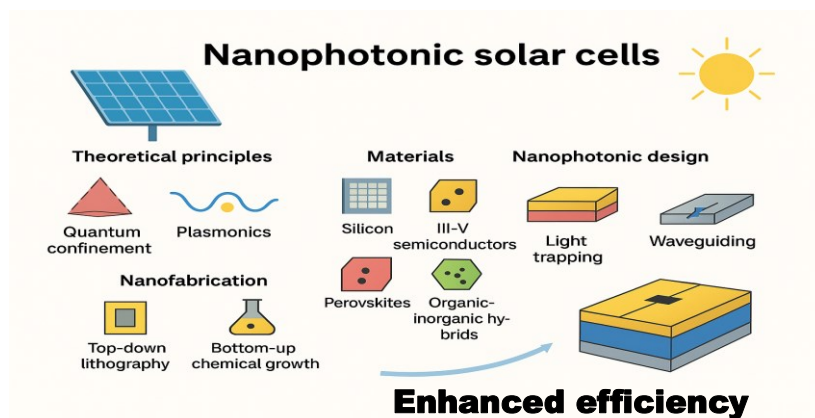
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Abstract- The advancement of nanostructured and nanophotonic solar cells represents a transformative pathway toward overcoming the fundamental limitations of conventional photovoltaic devices. This paper presents a comprehensive review of recent progress in theoretical principles, materials engineering, nanofabrication strategies, and device architectures that collectively aim to enhance solar energy conversion efficiency. Beginning with an exploration of quantum confinement, plasmonics, and hot-carrier mechanisms, the study highlights how nanoscale engineering enables bandgap tunability, improved spectral matching, and extended absorption beyond bulk semiconductor limits. Key classes of materials, including silicon, III–V semiconductors, perovskites, and emerging organic–inorganic hybrids, are critically assessed in relation to their compatibility with nanostructuring approaches. Fabrication techniques spanning top-down lithography, bottom-up chemical growth, and hybrid roll-to-roll imprinting are evaluated for scalability, precision, and industrial applicability. Nanophotonic design strategies, such as light trapping, waveguiding, and integration of plasmonic and photonic crystal structures, are shown to significantly enhance absorption and carrier collection in thin-film and tandem architectures. Performance benchmarks demonstrate that perovskite/silicon tandems and III–V multi-junction concentrators, when coupled with nanophotonic layers, are achieving efficiencies above 30% and approaching theoretical maxima. Despite these advances, critical challenges remain, particularly in fabrication cost, long-term stability, and large-area uniformity. Emerging solutions, including computational inverse design, scalable nanoimprint lithography, and durable material systems, indicate a clear trajectory toward commercial viability. This review underscores that nanophotonics is poised to accelerate the transition of solar technologies from laboratory-scale demonstrations to high-efficiency, industrial-scale deployment in the coming decade.

Graphical Abstract



Article Key Information

Keywords: Nanophotonic solar cells; Light trapping; Plasmonics; Perovskite photovoltaics; Tandem architectures; Scalable nanofabrication

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1. Introduction

Meeting the relentless global demand for sustainable and clean energy has become one of the most critical scientific and technological challenges of our time. Solar energy, as the most abundant renewable energy source available, holds immense promise for mitigating greenhouse gas emissions and ensuring energy security across the globe. Yet, conventional silicon-based photovoltaic (PV) technologies, while mature and widely deployed, face fundamental limitations in efficiency, cost reduction, and adaptability to emerging applications [1]. The Shockley–Queisser limit constrains the theoretical maximum efficiency of single-junction silicon cells to approximately 33%, and practical implementations often yield much lower efficiencies at non-trivial expense [2]. These constraints highlight the necessity of transformative research paradigms that can circumvent such bottlenecks through interdisciplinary innovation.

In recent years, nanostructured solar cells have emerged as a powerful strategy for addressing these challenges. By tailoring materials and architectures at the nanoscale, it is possible to significantly enhance light harvesting, promote efficient charge transport, and reduce material consumption, hence lowering both capital and material costs while boosting performance [3]. For example, nanostructured approaches have enabled advanced light-trapping in silicon cells and facilitated the use of quantum dot (QD) thin films for infrared absorption, promising higher efficiency at lower cost [3]. Additionally, silicon nanowire-based solar cells have shown remarkable improvements in power conversion efficiency, rising from below 1% to above 17% in recent experimental studies demonstrating the dramatic performance gains achievable through nanoscale structuring [4].

Central to the advent of high-performance nanostructured PV is the development of quantum materials. These are materials whose electronic and optical properties are strongly influenced by quantum confinement effects, enabling novel mechanisms for light absorption and carrier generation. Quantum dots, for instance, can exhibit multiple-exciton generation processes, exceeding the traditional one-photon–one-exciton paradigm and unlocking the potential for enhanced conversion efficiency [5]. Perovskite-based PV materials have experienced one of the fastest improvements in any photovoltaic technology, with laboratory-scale single-junction devices reaching efficiencies beyond 25.7% and tandem silicon–perovskite configurations approaching nearly 30% [6]. Moreover, alternative quantum materials such as transition-metal dichalcogenides and graphene derivatives continue to expand the design space for optoelectronic functionalities and interface engineering [7].

Beyond material innovation, nanotechnology-driven device engineering plays a critical role. Nanostructures such as nanopillars can triple light absorption efficiency by concentrating incident photons via tapered geometries optimized for light trapping [8]; similarly, multi-junction architectures incorporating quantum wells (QWs) enable graded bandgap absorption across the solar spectrum, with record multi-junction devices reaching efficiencies up to 46% under concentrated illumination [9]. Interface engineering using graphene-based derivatives has demonstrated significant improvements in perovskite solar cell performance by enhancing charge transport, passivating defects, and improving film morphology and stability [10,11]. These developments underscore how nanoscale design and hybrid material integration can revolutionize device performance.

Effective coupling of advanced nanomaterials and device architectures with power electronics and smart system integration is indispensable for realizing practical, high-efficiency solar energy generation. Energy harvesting from nanostructured solar cells must be complemented by efficient power conversion, maximum power point tracking (MPPT), and grid-oriented inverters. Although high-precision electronics are often developed separately, integrating these functionalities with the unique output characteristics of nanostructured PV systems remains a research gap, particularly in resource-constrained contexts. The nascent field of *photovoltaics* envisions such convergence, combining photovoltaics, electronics, sensing, and communications to create autonomous systems that harness both energy and information from photons [12].

Despite rapid advancements, several key challenges remain. Stability and durability continue to plague next-generation PV technologies. Perovskite solar cells, for instance, remain susceptible to degradation from moisture, UV exposure, and thermal stress [13]. Toxicity concerns, particularly with lead-based perovskites and heavy-metal-based quantum dots, impede safe commercialization and necessitate replacements with eco-friendly alternatives such as tin-based perovskites or lead-free quantum dots [14]. Moreover, scalability and large-area manufacturing of nanostructured devices present serious cost and engineering hurdles, as performance gains often stem from laboratory-scale fabrication not always transferable to industrial production. Finally, there exists a notable disconnect between material/device researchers and power electronics/system integrators, limiting the fruition of end-to-end high-efficiency systems.

This review aims to bridge these disciplinary silos by providing a comprehensive examination of three converging domains: (1) Quantum materials, including perovskites, quantum dots, graphene derivatives; (2) Nanotechnology-enabled device engineering, covering nanowires, nanopillars, multi-junction architectures, and interface engineering; and (3) Power electronics for system integration, emphasizing MPPT, inverters, and smart grid connectivity frameworks. Through critical synthesis of recent breakthroughs (2018–2025) and identification of current challenges, this review will:

- Examine how quantum materials advance light absorption, charge generation, and tunability.
- Analyze nanostructured architectures and fabrication strategies that enhance efficiency.
- Explore the synergy of power electronics with nanoscale PV devices toward integrated, high-efficiency systems.
- Highlight sustainability, scalability, and application-driven challenges, especially relevant to emerging economies.
- Suggest future directions such as eco-friendly material development, AI-guided design, and decentralized energy-smart nanophotovoltaic platforms.

By systematically combining these perspectives, this review seeks to foster an interdisciplinary roadmap for the evolution of energy-efficient nanostructured solar technologies, ultimately accelerating their translation into high-impact applications and global energy solutions.

2. Theoretical Foundations of Nanostructured Solar Cells

The efficiency of photovoltaic devices is fundamentally limited by thermodynamic, optical, and electronic constraints. Traditional planar solar cells, based on bulk semiconductor layers, are restricted by the Shockley–Queisser limit, which sets a theoretical maximum efficiency of about 33% for single-junction cells under standard solar illumination [12]. Overcoming this limit requires advanced strategies that manipulate light–matter interactions at the nanoscale, enabling more effective harvesting of the solar spectrum.

2.1 Quantum Confinement and Bandgap Engineering

At the nanoscale, the quantum confinement effect modifies the density of electronic states, allowing tuning of the semiconductor bandgap by controlling nanocrystal size [13]. This tunability enables better spectral matching to solar radiation and paves the way for multi-exciton generation, where a single high-energy photon generates multiple charge carriers, thereby enhancing theoretical efficiency beyond bulk limitations [14]. The impact of these mechanisms is summarized in Table 1, which outlines the major theoretical pathways to enhanced photovoltaic performance.

Table 1. Summary of theoretical principles enabling efficiency enhancement in nanostructured solar cells

Mechanism	Description	Impact on Efficiency
Quantum confinement	Bandgap tunability through nanocrystal size	Enhanced spectral matching, multi-exciton generation
Light trapping & scattering	Increased optical path length via nanostructures	Improved absorption in thin films
Plasmonics	Electromagnetic field enhancement via nanoparticles	Stronger absorption, photocurrent boost
Hot carrier effects	Extraction before thermalization	Higher carrier energy utilization
Intermediate band formation	Sub-bandgap photon absorption	Broader solar spectrum use
Tandem/multi-junction	Layered absorbers with tailored bandgaps	Efficiencies >40% achievable

2.2 Light Trapping and Scattering

Nanostructured architectures, such as nanowires, photonic crystals, and textured surfaces, enhance light absorption by increasing the optical path length within the active material [15]. By scattering and trapping light, these structures mimic natural light-harvesting mechanisms, effectively increasing absorption without increasing material thickness. The contrast between planar and nanostructured absorption schemes is illustrated in Figure 1, which shows how nanostructures extend the optical path length through scattering, waveguiding, and resonant effects.

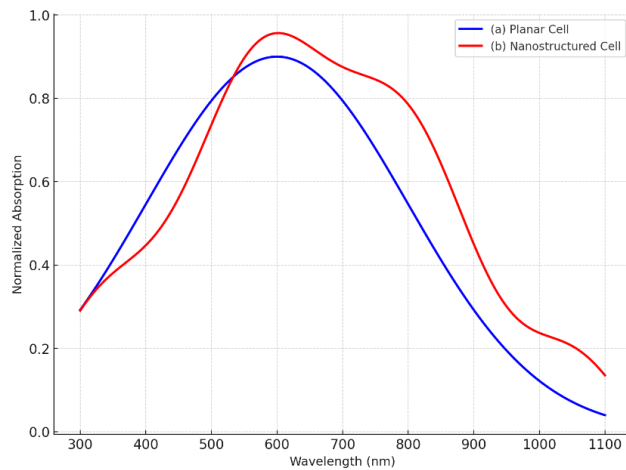


Figure 1. Schematic of light absorption in (a) planar and (b) nanostructured solar cells. Nanostructures enhance absorption via scattering, waveguiding, and localized plasmon resonances.

2.3 Plasmonics and Localized Surface Resonances

Incorporating metallic nanoparticles introduces plasmonic effects that concentrate electromagnetic fields at the nanoscale [16]. Localized surface plasmon resonances (LSPRs) can increase the effective absorption cross-section of nearby semiconductors, enhancing both absorption and photocurrent generation. These effects are highly dependent on nanoparticle geometry, size, and surrounding dielectric environment [17].

2.4 Hot Carrier and Intermediate Band Mechanisms

Beyond conventional absorption, nanostructures enable hot carrier extraction and intermediate band formation [18]. Hot carrier solar cells aim to harness energetic carriers before they lose energy via thermalization, while intermediate band materials allow absorption of sub-bandgap photons, extending the usable portion of the solar spectrum [19].

2.5 Integration of Multi-Junction and Tandem Architectures

Theoretical efficiency improvements also rely on tandem and multi-junction configurations, where nanostructured layers are stacked to absorb different portions of the solar spectrum [20]. These designs capitalize on bandgap tunability and light-trapping effects, offering pathways to efficiencies exceeding 40% under concentrated sunlight.

3.0 Materials and Nanofabrication Approaches

The advancement of nanostructured solar cells relies heavily on material selection and fabrication techniques that enable precise control of nanoscale features. The interplay between material properties and fabrication methods dictates light absorption, charge transport, and overall device stability. In this section, we review the primary classes of materials and state-of-the-art nanofabrication approaches, integrating their relevance to photovoltaic performance.

3.1 Semiconductor Materials for Nanostructured Solar Cells

Silicon remains the backbone of the photovoltaic industry due to its abundance, well-understood processing, and stable performance. However, its indirect bandgap limits absorption in thin layers, necessitating nanostructuring for enhanced light trapping [21]. Compound semiconductors such as GaAs, InP, and CdTe offer direct bandgaps with higher absorption coefficients, making them attractive for thin-film nanostructures [22]. More recently, perovskite materials have emerged with tunable bandgaps, solution processability, and strong absorption, showing remarkable promise when integrated into nanostructured architectures [23].

These material classes are systematically compared in Table 2, which highlights their bandgap ranges, absorption properties, and compatibility with nanofabrication techniques.

Table 2. Comparative summary of materials used in nanostructured solar cells and their properties

Material Class	Bandgap (eV)	Key Advantages	Nanostructure Compatibility
Silicon (Si)	1.1	Abundant, mature technology	Requires nanostructuring for strong absorption
GaAs, InP, CdTe	1.3–1.5	Direct bandgap, high efficiency	Compatible with nanowires, thin films
Perovskites (e.g., MAPbI ₃)	1.5–2.3	Tunable bandgap, solution processable	Easily integrated into nanostructures
Organic semiconductors	1.7–2.2	Lightweight, flexible	Nanostructured bulk heterojunctions
Metal nanostructures (Au, Ag, Al)	-	Plasmonic enhancement, hot electron effects	Incorporated as nanoparticles, gratings

3.2 Metallic and Plasmonic Nanostructures

In addition to semiconductors, metals such as gold, silver, and aluminum are frequently introduced in the form of nanoparticles, gratings, or thin films to exploit plasmonic effects [24]. The localized surface plasmon resonances (LSPRs) generated by these nanostructures not only enhance absorption in adjacent semiconductors but also provide pathways for hot electron injection [25]. Optimizing nanoparticle geometry and placement is crucial to avoid parasitic absorption losses.

3.3 Nanofabrication Techniques

The realization of nanoscale architectures requires fabrication methods that combine precision, scalability, and cost-effectiveness. Top-down techniques such as electron-beam lithography, focused ion beam milling, and nanoimprint lithography provide high-resolution patterning but can be expensive for large-scale deployment [26]. In contrast, bottom-up approaches such as chemical vapor deposition (CVD), atomic layer deposition (ALD), and solution-based self-assembly offer scalability with lower costs, albeit with less control over uniformity [27].

Figure 2 schematically illustrates some representative fabrication routes, contrasting top-down lithographic patterning with bottom-up chemical growth approaches.

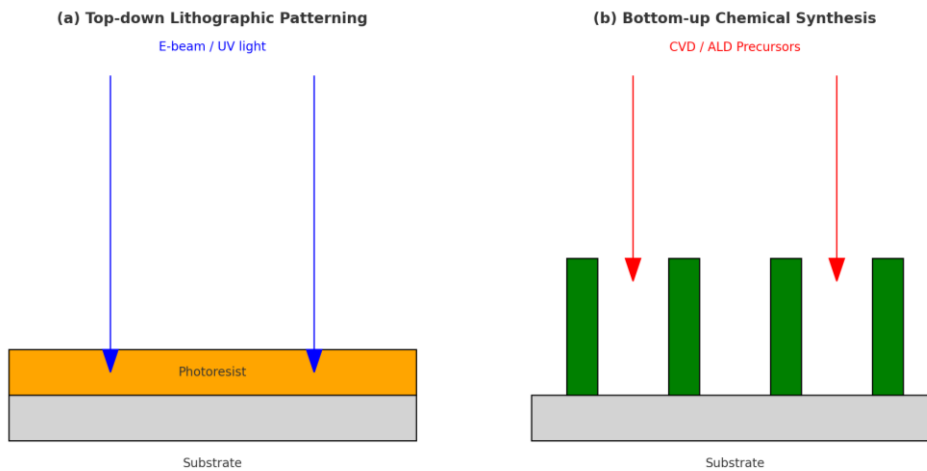


Figure 2. Representative nanofabrication approaches: (a) top-down lithographic patterning (e.g., e-beam, nanoimprint), and (b) bottom-up chemical synthesis (e.g., ALD, CVD, solution-based growth).

3.4 Hybrid and Emerging Fabrication Approaches

Hybrid approaches that integrate lithography with self-assembly, or combine perovskite solution processing with nanostructured silicon templates, are gaining attention [28]. Furthermore, emerging methods such as additive manufacturing (3D printing of functional nanomaterials) and roll-to-roll nanofabrication open pathways for scalable, flexible solar cell production [29]. These innovations aim to reduce cost while maintaining nanoscale precision.

4. Nanophotonic Design Strategies for Enhanced Solar Energy Conversion

Nanophotonic engineering provides a versatile toolbox for manipulating light at sub-wavelength scales, offering unique strategies to surpass the conventional limitations of photovoltaic devices. By controlling light-matter interactions through structural design, nanophotonic concepts can enhance absorption, extend spectral response, and improve carrier collection efficiency in solar cells. Three main categories of nanophotonic strategies dominate current research: light trapping and waveguiding, plasmonic enhancement, and photonic crystal/metasurface integration.

4.1 Light Trapping and Waveguiding

Light trapping mechanisms aim to confine photons within the absorber layer, thereby increasing the probability of absorption without increasing material thickness. Traditional methods, such as surface texturing, improve path length, but nanostructures enable far more sophisticated control. For instance, nanowires, nanocones, and gratings create guided resonances that redirect incident light into lateral waveguide modes, effectively boosting the optical path length [30].

Figure 3 illustrates the principle: in a planar absorber, incident light often transmits or reflects, whereas nanostructured layers scatter photons into guided modes, leading to stronger absorption across the visible and near-infrared spectrum. This approach is especially important for thin-film solar technologies, where maintaining both mechanical flexibility and high absorption is critical [31].

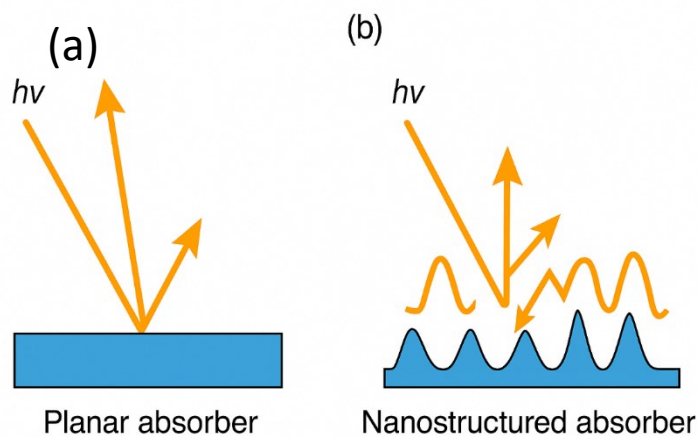


Figure 3. Schematic of light trapping in (a) planar absorber, where light passes through with limited interaction, and (b) nanostructured absorber, where scattering, waveguiding, and plasmonic effects enhance optical path length and absorption efficiency.

4.2 Plasmonic Enhancement

Plasmonic nanostructures exploit the oscillations of free electrons in metallic nanoparticles (NPs) or nanostrips to concentrate electromagnetic fields near the absorber. Localized surface plasmon resonances (LSPRs) produce intense near-field enhancement, which can be coupled directly into the semiconductor to improve absorption at wavelengths near the plasmonic resonance [32].

Gold (Au) and silver (Ag) nanoparticles are widely employed due to their tunable plasmonic response in the visible range, while aluminum (Al) is gaining interest for ultraviolet plasmonics owing to its abundance and lower cost [33]. Table 3 summarizes representative plasmonic materials and their optimal application ranges in photovoltaic devices.

Table 3. Representative plasmonic materials for solar cell integration.

Material	Plasmon Resonance Range	Application in PV	Remarks
Au	Visible – NIR	Thin-film Si, perovskite solar cells	Stable but expensive
Ag	Visible	Organic PV, dye-sensitized cells	Strong resonance, but prone to oxidation
Al	UV – Visible	GaN, perovskites	Low cost, CMOS-compatible
Cu	Visible – NIR	Emerging thin-film technologies	Abundant, but less stable

4.3 Photonic Crystals and Metasurfaces

Photonic crystals and metasurfaces allow precise control of photonic band structures and light propagation through engineered periodicity. Unlike random scatterers, these ordered nanostructures can achieve selective spectral filtering, angular confinement, and broadband absorption simultaneously [34].

For example, two-dimensional photonic crystals integrated onto thin-film solar cells enhance efficiency by opening photonic bandgaps that inhibit reflection and recycle photons back into the absorber [35]. Similarly, dielectric metasurfaces composed of silicon or titanium dioxide can be tailored to exhibit Mie resonances, enhancing forward scattering while minimizing parasitic losses [36].

Figure 4 schematically compares a conventional antireflection coating with a nanophotonic metasurface, highlighting the sharper spectral control and stronger light localization achievable with metasurface designs.

4.4 Synergistic Strategies

The most promising pathway involves hybridizing these approaches. For example, embedding plasmonic nanoparticles within a photonic crystal can simultaneously exploit near-field enhancement and long-range photon recycling [37]. Such synergy has been reported in perovskite solar cells, where coupling between LSPRs and guided-mode resonances achieved power conversion efficiencies beyond those of single-mechanism devices [38].

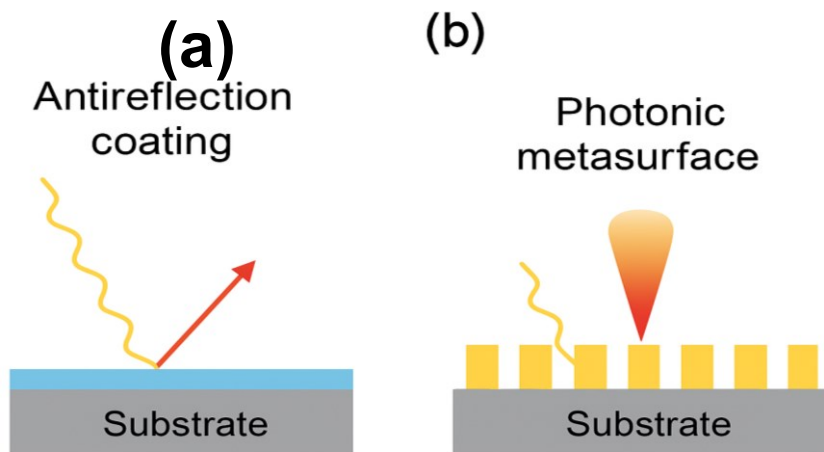


Figure 4. Schematic comparison of (a) conventional antireflection coating, which reduces surface reflection over a limited spectral range, and (b) nanophotonic metasurface, which enables sharper spectral control and stronger light localization for enhanced absorption.

Future design paradigms emphasize computationally guided nanophotonic architectures, using machine learning and inverse design algorithms to optimize geometries beyond conventional human intuition [39]. These methods accelerate the discovery of photonic structures that balance optical enhancement with manufacturability.

5. Device Architectures and Performance Trends

The integration of nanophotonic strategies into photovoltaic (PV) devices has led to the emergence of diverse solar cell architectures, each optimized for light management, carrier extraction, and manufacturability [40]. In conventional planar devices, optical losses are predominantly dictated by front-surface reflection and incomplete absorption in thin active layers [12,41]. By contrast, nanostructured designs including plasmonic, dielectric, and photonic crystal approaches enable superior light trapping and broadband absorption, directly influencing external quantum efficiency (EQE) and power conversion efficiency (PCE) [42–44].

5.1 Thin-Film Solar Cells with Nanostructures

Thin-film technologies such as amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) inherently suffer from limited absorption in sub-micron layers. Introducing nanostructured front electrodes (e.g., nanowire or nanopillar arrays) has been shown to significantly enhance optical path lengths while simultaneously reducing reflection [45,46]. For instance, textured indium tin oxide (ITO) front layers act as both transparent electrodes and scattering centers, leading to improved current densities in a-Si:H cells [47]. Figure 5 illustrates a representative comparison between conventional planar thin-film and nanostructured thin-film solar cells, highlighting differences in light absorption profiles.

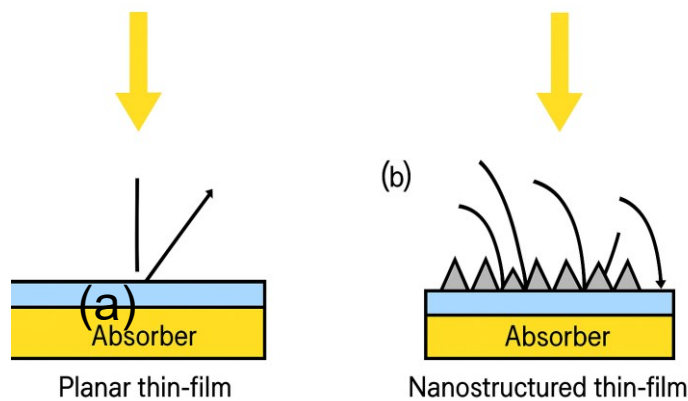


Figure 5. Schematic comparison between (a) planar thin-film solar cell with limited absorption and (b) nanostructured thin-film solar cell with enhanced scattering and light trapping.

5.2 Multi-Junction and Tandem Architectures

Tandem solar cells, comprising multiple sub-cells with complementary bandgaps, offer a pathway to surpass the Shockley–Queisser limit (~33% for single junctions) [48]. Incorporating nanophotonic layers such as dielectric metasurfaces for spectrum splitting or plasmonic back reflectors for sub-bandgap light trapping has enabled tandem devices to approach efficiencies beyond 40% under concentrated illumination [49,50]. For example, perovskite/silicon tandem cells have achieved certified PCEs exceeding 32% [51], driven by optimized optical management at the perovskite/silicon interface [52]. Table 3 summarizes reported efficiency benchmarks for leading nanostructured device architectures.

Table 3. Reported efficiency trends in nanostructured solar cell architectures.

Device Architecture	Key Nanophotonic Strategy	Reported PCE (%)	Reference
Planar a-Si:H thin-film	Textured TCO front electrodes	12.5	[47]
Nanostructured CdTe thin-film	Nanopatterned back reflectors	19.0	[45]
Plasmonic-enhanced CIGS	Embedded Ag nanoparticles	20.4	[46]
Perovskite/Si tandem	Dielectric metasurface for spectrum management	32.5	[51]
III-V multi-junction concentrator	Photonic crystal light trapping	41.1	[49]

5.3 Emerging Device Configurations

Emerging architectures such as bifacial, semi-transparent, and flexible solar cells also benefit substantially from nanophotonic engineering. Bifacial designs, for example, integrate nanostructured rear reflectors to capture albedo light, improving energy yield by up to 30% in field conditions [53]. Semi-transparent perovskite cells leverage dielectric nanostructures for tailored spectral selectivity, enabling applications in building-integrated photovoltaics (BIPV) [54]. Meanwhile, flexible devices employing nanostructured polymer substrates exhibit enhanced light scattering, addressing the trade-off between optical performance and mechanical compliance [55].

Collectively, these architectural advances demonstrate that nanophotonics not only enhances device-level absorption but also enables entirely new solar cell functionalities. Beyond performance, the choice of architecture is increasingly being shaped by scalability, cost, and compatibility with existing PV manufacturing platforms [56]. The following section will discuss persisting challenges and the future outlook for nanophotonic photovoltaics.

6. Challenges, Limitations, and Future Outlook

Despite remarkable advances in integrating nanostructures into solar cells, several fundamental and practical challenges must be addressed before widespread commercialization can be achieved. These challenges span from fabrication scalability and cost-effectiveness to long-term material stability and environmental impact.

6.1 Fabrication Complexity and Scalability

One of the foremost limitations lies in the complexity and cost of nanofabrication methods. While techniques such as electron-beam lithography and focused ion beam milling provide high-resolution nanostructures, they are prohibitively slow and expensive for large-area solar modules [57,58]. Bottom-up approaches, including colloidal self-assembly and chemical vapor deposition, offer more scalable routes but often suffer from poor uniformity and reproducibility over wafer-scale substrates [59]. Bridging the gap between nanoscale precision and large-area manufacturability remains a major hurdle. Emerging hybrid techniques, such as nanoimprint lithography and roll-to-roll nano-patterning, show promise for scalable integration, but require optimization for industrial throughput [60].

6.2 Optical vs. Electrical Trade-offs

Nanostructures designed for enhanced optical absorption often introduce unintended electrical penalties. For instance, high-aspect-ratio nanowires or nanocones may improve light trapping, but they can also increase surface recombination due to large surface-to-volume ratios [61]. Similarly, plasmonic nanoparticles can introduce parasitic absorption and Joule heating, counteracting optical gains [62]. This optical–electrical trade-off necessitates careful design optimization to balance photonic enhancement with electronic quality.

6.3 Material Stability and Degradation

Material stability is another critical barrier to commercialization. Many high-performing nanostructures rely on noble metals (e.g., Ag, Au) for plasmonic enhancement, yet these materials are prone to oxidation, diffusion, and morphological degradation under prolonged illumination [63]. Similarly, perovskite-based nanostructured solar cells exhibit remarkable efficiency but face rapid degradation from moisture, oxygen, and UV exposure [64]. Protective encapsulation and stable nanophotonic materials (e.g., TiN, doped oxides) are being explored as durable alternatives [65].

6.4 Environmental and Economic Considerations

Beyond technical challenges, the environmental sustainability and economic feasibility of nanostructured solar cells are critical. Large-scale deployment of noble metals and rare materials may lead to cost inflation and supply-chain constraints [66]. Moreover, the environmental footprint of energy-intensive nanofabrication techniques raises concerns about whether such approaches can truly contribute to sustainable energy solutions [67]. Future research should prioritize green synthesis methods, recyclable nanostructured components, and life-cycle analyses to ensure net-positive energy returns.

6.5 Future Outlook: Towards Commercialization

Looking forward, the field is moving towards multifunctional nanophotonic solar cells that combine light trapping, spectral selectivity, and thermal management within a single platform [68]. Integration of metasurfaces capable of dynamic tuning could allow solar cells to adapt to changing illumination conditions [69]. Furthermore, tandem architectures that stack nanostructured perovskite layers atop crystalline silicon are demonstrating efficiencies exceeding 30%, pointing to realistic commercialization pathways [70]. Finally, advances in computational design, particularly through machine learning and inverse design algorithms, are expected to accelerate the discovery of optimal nanophotonic architectures beyond intuitive trial-and-error approaches [71].

6.6 Summary of Challenges and Opportunities

Table 4 summarizes the key limitations currently impeding nanophotonic solar cells and highlights emerging solutions that may overcome these barriers. To provide a broader perspective, Figure 6 presents a conceptual roadmap that links the major challenges, such as fabrication complexity, material stability, and cost barriers, to potential technological solutions and their corresponding commercialization pathways. This visual framework emphasizes that overcoming nanoscale-to-industry scale transitions requires not only technical innovation but also integration with scalable manufacturing and market-driven strategies.

Table 4. Summary of challenges in nanostructured solar cells and potential research directions.

Challenge	Impact	Emerging Solutions
High fabrication cost & complexity	Limits scalability	Nanoimprint lithography, roll-to-roll patterning
Optical–electrical trade-offs	Reduced efficiency	Surface passivation, optimized nanogeometries
Material degradation (e.g., metals, perovskites)	Long-term instability	Durable alternatives (TiN, oxides), encapsulation
Resource and environmental concerns	Economic/environmental unsustainability	Green synthesis, recyclable nanostructures
Lack of adaptive light management	Suboptimal under variable conditions	Tunable metasurfaces, adaptive nanophotonics

In summary, while nanophotonic solar cells face significant fabrication, stability, and economic challenges, ongoing innovations in scalable nanomanufacturing, durable materials, and computationally guided design are rapidly closing the gap between laboratory demonstrations and industrial adoption. Together, Table 4 and Figure 6 underscore that the next decade is likely to witness the transition of nanostructured solar cells from proof-of-concept devices to real-world deployment, marking a decisive step toward high-efficiency and sustainable photovoltaic technologies.

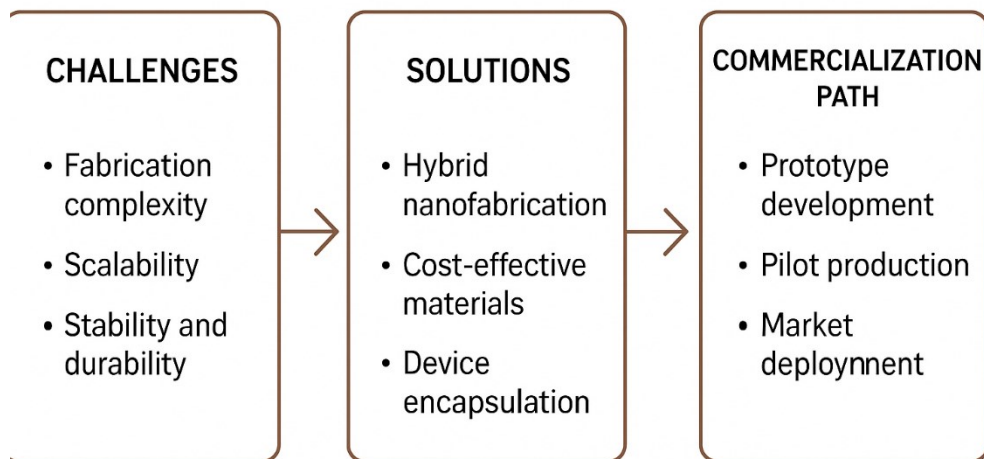


Figure 6. Conceptual roadmap for nanophotonic solar cells, illustrating the transition from current challenges (e.g., fabrication complexity, stability issues, and high cost) toward emerging solutions (scalable nanomanufacturing, durable material design, and computational optimization) and eventual commercialization pathways.

Complementary solutions addressing these limitations are summarized in **Table 4**, reinforcing how integrated innovation can accelerate the deployment of nanostructured photovoltaic technologies from laboratory-scale demonstrations to industrial-scale applications.

7.0 Conclusion and Future Perspectives

7.1 Conclusion

Nanophotonic solar cells represent one of the most promising frontiers in photovoltaic research, offering pathways to overcome the fundamental efficiency and stability limitations of conventional devices. This review has shown that by harnessing advanced light management strategies, integrating novel semiconductors, and adopting scalable nanofabrication approaches, significant gains in absorption, carrier transport, and overall performance can be achieved. While challenges remain in fabrication cost, material durability, and large-area integration, recent progress suggests that these barriers are steadily being reduced.

7.2 Future Outlook

The future development of nanophotonic photovoltaics will depend on the convergence of scalable fabrication, durable materials, and computationally guided design. In particular, hybrid lithography, roll-to-roll patterning, and additive manufacturing are expected to accelerate the transition from laboratory-scale devices to commercial deployment. Improvements in perovskite stability, plasmonic alternatives, and defect passivation will further strengthen device reliability, a prerequisite for long-term application. Artificial intelligence and inverse design are anticipated to play a central role in accelerating innovation, enabling the discovery of novel architectures beyond conventional intuition. Looking ahead, nanophotonic solar cells are likely to extend their impact beyond traditional energy harvesting into applications such as building-integrated photovoltaics, wearable energy systems, and photonic–electronic hybrid devices.

7.3 Recommendations

Future work should emphasize bridging nanoscale precision with large-area manufacturing, developing stable and sustainable materials for long-term device performance, and strengthening collaboration between academia and industry. Such coordinated efforts will ensure that nanophotonic solar cells evolve from promising laboratory prototypes into commercially viable technologies capable of supporting the global clean energy transition.

Declarations

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Approval

Not applicable. This article does not contain any studies with human participants or animals performed by any of the authors.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions

Mbakaan Celestine: Conceptualization, methodology, investigation, writing original draft preparation. Kpelai Justine A, Abah Inalegwu S, and Atagher Peter: Validation, resources, editing, and supervision. All authors have read and approved the final manuscript.

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