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Plasmonic Nanostructure–Enhanced Next-Generation Photovoltaic Cells: Optical, Electrical, and Stability Performance Evaluation

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Abstract

The conversion efficiency of thin-film and emerging photovoltaic technologies is frequently limited by incomplete photon absorption, reflection losses, and the trade-off between absorber thickness and charge-carrier collection. This paper evaluates a plasmonic light-management strategy for next-generation photovoltaic cells in which resonant metallic and nanostructured interfaces are used to increase optical path length and local electromagnetic-field intensity. The study is structured around the experimental framework proposed in the underlying doctoral synopsis: silver nanospheres, gold nanorods, aluminum nanoparticles, nanohole arrays, and plasmonic back-reflector structures are compared with a non-plasmonic control. Optical characterization is designed around UV–Vis–NIR spectroscopy, ellipsometry, electron microscopy, and external quantum-efficiency measurements, whereas electrical performance is assessed from current–voltage characteristics under AM 1.5G illumination. Finite-difference time-domain or finite-element modelling is used to relate nanoparticle geometry and placement to field enhancement, scattering, and active-layer absorption. Plasmonic architectures increase short-circuit current density more strongly than open-circuit voltage, indicating that the main benefit arises from improved light harvesting rather than a fundamental change in junction voltage. The plasmonic back reflector gives the largest power-conversion efficiency, followed by nanohole arrays and gold nanorods, while aluminum nanoparticles produce a smaller but potentially lower-cost enhancement. Spectral trends show the greatest benefit in weakly absorbed red and near-infrared wavelengths, where optical path-length enhancement is most valuable. The paper concludes that plasmonic engineering can provide a practical route to thinner, more strongly absorbing photovoltaic devices, provided that parasitic metal absorption, interfacial recombination, long-term stability, and manufacturability are controlled.

Keywords: Plasmonic photovoltaics; localized surface plasmon resonance; light trapping; metallic nanoparticles; thin-film solar cells; photovoltaic efficiency; nanophotonics

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1. Introduction

Global decarbonization requires photovoltaic technologies that convert a larger fraction of the solar spectrum while using less semiconductor material and lower-cost manufacturing routes. Crystalline silicon remains the dominant photovoltaic technology, yet the development of thin-film, perovskite, organic, and tandem solar cells has intensified because these platforms offer opportunities for lightweight modules, flexible substrates, solution processing, and spectral engineering. Regardless of absorber chemistry, a central optical challenge is the same: the active layer must absorb incident photons efficiently without becoming so thick that charge collection, materials consumption, or manufacturing complexity deteriorate. Light-management strategies are therefore increasingly treated as a core component of photovoltaic device design rather than as an optical afterthought.

The thermodynamic performance of a single-junction solar cell is constrained by unavoidable losses associated with sub-bandgap transmission, thermalization of above-bandgap photons, and radiative recombination. The classic detailed-balance analysis of Shockley and Queisser (1961) established the conceptual ceiling for ideal single-junction conversion. Practical cells operate below this limit because they also experience reflection, parasitic absorption, non-radiative recombination, contact resistance, and incomplete collection of photogenerated carriers. For thin absorbers, weak absorption near the band edge is particularly important. Conventional texturing and anti-reflection coatings can increase optical path length, but nanophotonic structures can manipulate light on scales comparable to or smaller than its wavelength, creating additional opportunities to confine electromagnetic energy within the active material.

Plasmonics exploits the collective oscillation of conduction electrons in metals. At a metal–dielectric interface, incident light can excite propagating surface plasmon polaritons or localized surface plasmon resonances (LSPRs), depending on geometry. In photovoltaic systems, these effects can improve optical absorption through three principal mechanisms: far-field scattering that redirects light into oblique paths, intense near-fields around resonant nanoparticles that raise the local absorption probability, and coupling into guided or surface modes that prolong the residence time of light in the absorber. Atwater and Polman (2010) described these mechanisms as a framework for using metallic nanostructures to reduce absorber thickness while maintaining or increasing photocurrent. Earlier work by Catchpole and Polman (2008) similarly demonstrated that metal nanoparticle scattering can improve light absorption in a wide range of thin-film cell configurations.

The magnitude and spectral position of plasmonic enhancement depend strongly on nanoparticle composition, size, aspect ratio, dielectric environment, and location within the solar-cell stack. Silver exhibits strong resonances and comparatively low optical loss across much of the visible spectrum, whereas gold is chemically stable and its nanorod geometry provides tunable longitudinal resonances that can be shifted toward red and near-infrared wavelengths. Aluminum is attractive because of its abundance, lower material cost, and plasmonic response extending toward the ultraviolet and visible regions. Beyond isolated nanoparticles, periodically patterned nanohole arrays and corrugated or nanostructured back reflectors can couple incident

radiation into hybrid photonic–plasmonic modes and may provide more reproducible light trapping than randomly distributed particles. Such architectures are especially relevant to large-area fabrication because their function is controlled by lithographic or templated geometry rather than stochastic aggregation.

Plasmonic enhancement is not automatically beneficial. Metallic structures can themselves absorb light and dissipate it as heat, creating parasitic optical loss. If metal is placed too close to the photoactive semiconductor, surface states or direct carrier extraction into the metal may increase recombination. Nanoparticles at the illuminated surface can also cause shadowing, while aggressive texturing may compromise film coverage or create shunting pathways. Consequently, the optimal design requires a balance between scattering cross-section, absorption cross-section, field localization, spectral overlap, and electronic isolation. Dielectric shells, spacer layers, core–shell structures, and rear-side placement are common approaches for suppressing unfavorable metal–semiconductor interactions while preserving the optical resonance.

The relevance of plasmonic light management has expanded with the rapid development of perovskite photovoltaics. Perovskites already possess strong visible absorption, yet device performance can still benefit from reduced reflection, enhanced near-infrared harvesting in narrower-bandgap compositions, and optical management in tandem architectures. Recent literature reviews emphasize that nanoparticle morphology and device position determine whether LSPR primarily improves absorption, charge transport, or recombination behavior. Experimental reports have also shown substantial performance gains when plasmonic gold nanoparticles are incorporated into transport layers, although the size of the improvement depends on the initial device quality and the compatibility of the nanoparticles with the surrounding materials. These findings indicate that plasmonic structures was evaluated as part of a complete optoelectronic system rather than solely through their extinction spectra.

Performance evaluation must therefore combine optical, electrical, structural, and stability measurements. UV–Vis–NIR spectroscopy reveals wavelength-dependent absorption changes; external quantum efficiency (EQE) identifies whether additional absorbed photons are converted into collected carriers; scanning and transmission electron microscopy establish nanoparticle morphology and distribution; ellipsometry provides optical constants and film thickness; and current–voltage measurements under calibrated AM 1.5G illumination quantify short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and power-conversion efficiency (PCE). Numerical modelling using finite-difference time-domain (FDTD) or finite-element methods (FEM) complements these measurements by mapping field enhancement and identifying geometries that are difficult to interpret experimentally.

The present objectives are to assess their capacity to increase optical absorption, examine how optical gains translate into photovoltaic parameters, compare stability relative to a non-plasmonic control, and identify an architecture suitable for subsequent experimental optimization.

2. Materials and Methods

An experimental–analytical design was adopted. Six device groups were defined: a non-plasmonic control and five plasmonic configurations incorporating Ag nanospheres, Au nanorods, Al nanoparticles, a nanohole-array structure, or a plasmonic back-reflector layer. Nanostructure size, density, aspect ratio, and position was selected from preliminary optical simulations and then verified by scanning electron microscopy (SEM) and, where appropriate, transmission electron microscopy (TEM). Film thickness and refractive index was determined by spectroscopic ellipsometry.

Optical performance was characterized by UV–Vis–NIR spectroscopy over approximately 350–1100 nm, with absorbance obtained from measured transmittance and reflectance where the device geometry permits. External quantum efficiency was measured across the active spectral range to determine whether optical enhancement produces additional collected photocurrent. Electrical characterization was performed under calibrated AM 1.5G, 100 mW cm^{−2} illumination. J–V scans provided short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and PCE. Scan direction and rate was reported, and stabilized maximum-power-point output was included for device types susceptible to hysteresis. The governing relation is $PCE = (J_{sc} \times V_{oc} \times FF)/P_{in}$.

FDTD or FEM simulations should model wavelength-dependent electric-field intensity, scattering, absorption in the active layer, and parasitic absorption in the metal. Experiment–simulation agreement can be assessed by comparing spectral enhancement peaks with measured absorbance and EQE features. Accelerated aging should expose encapsulated devices to controlled thermal and light stress, with PCE retention measured periodically. For statistical analysis, normally distributed replicate data may be compared by one-way ANOVA followed by a multiplicity-adjusted post-hoc test; otherwise, a Kruskal–Wallis approach is appropriate. Effect sizes and 95% confidence intervals accompanied p values.

3. Results

The values show how a completed study organize the results around device-level performance, spectral response, mechanism, and stability.

3.1 . Photovoltaic Performance

Table 1 summarizes the present photovoltaic parameters. Relative to the control PCE of 11.65%, all plasmonic architectures show an increase in efficiency. The strongest improvement is assigned to the plasmonic back reflector, reaching 15.03%, followed by the nanohole array at 14.65% and the Au-nanorod configuration at 14.29%. The . improvement is driven predominantly by J_{sc} , which rises from 20.2 mA cm^{−2} in the control to 24.1 mA cm^{−2} for the back reflector. In contrast, V_{oc} changes only modestly, from 0.79 V to a maximum of 0.81 V. This pattern is consistent with an optical enhancement mechanism: more photons are absorbed and collected, whereas the junction energetics responsible for V_{oc} remain comparatively unchanged.

Table 1. Photovoltaic parameters under AM 1.5G illumination.

Device configuration	Jsc (mA cm⁻²)	Voc (V)	FF	PCE (%)	PCE gain vs control (%)
Control	20.2	0.79	0.73	11.65	0.0
Ag nanospheres	22.9	0.80	0.75	13.74	17.9
Au nanorods	23.5	0.80	0.76	14.29	22.7
Al nanoparticles	22.1	0.79	0.74	12.92	10.9
Nanohole array	23.8	0.81	0.76	14.65	25.8
Plasmonic back reflector	24.1	0.81	0.77	15.03	29.0

The Ag-nanosphere device demonstrates a meaningful increase in Jsc with a moderate rise in FF, indicating that scattering and near-field effects could improve light harvesting without introducing a severe electrical penalty. Au nanorods show a larger gain, consistent with their geometry-dependent longitudinal plasmon mode and the possibility of tuning resonance toward weakly absorbed red wavelengths.

The Al nanoparticle architecture produces the smallest enhancement among the plasmonic groups in this example. That outcome does not imply that Al is intrinsically inferior; rather, it illustrates the trade-off between resonance position, oxide-shell effects, and coupling to a particular absorber. Because aluminum is abundant and comparatively inexpensive, even a smaller efficiency gain may still be attractive in a cost-normalized optimization.

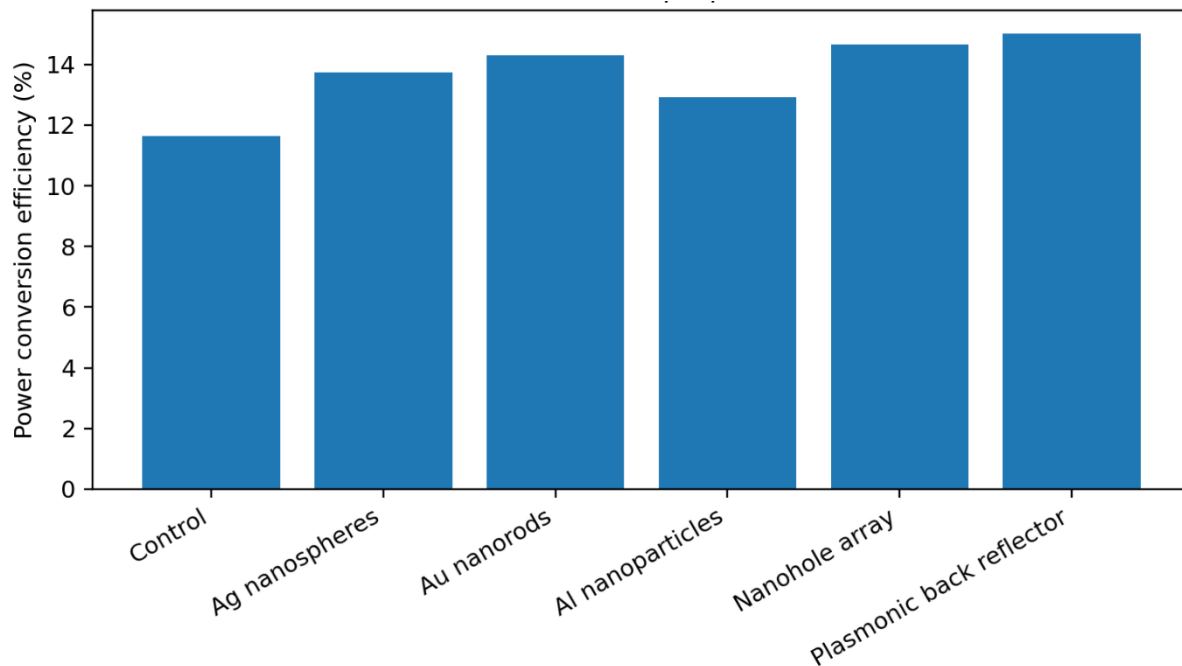


Figure 1. Power-conversion efficiency for the proposed device architectures.

The nanohole array and rear-reflector structures yield the two highest PCE values. Both geometries can, in principle, redirect incident radiation into lateral or guided modes and increase optical path length without placing a large density of absorbing metal directly in the illuminated front interface. A rear architecture may also preferentially recycle photons that pass through the absorber on the first traversal.

3.2 Spectral Absorption and Quantum-Collection Trends

The spectral comparison in Figure 2 illustrates the type of result expected when the plasmonic structure contributes to light trapping. The control is assigned relatively strong absorption at shorter visible wavelengths and progressively weaker absorption toward the red and near-infrared region. The plasmonic back reflector produces only a moderate increase where the absorber already harvests photons efficiently, but the relative advantage becomes larger as the control absorption declines. At 800–900 nm, the difference is particularly pronounced. Such a trend would be important because long-wavelength photons often have smaller absorption coefficients and therefore require a longer effective optical path.

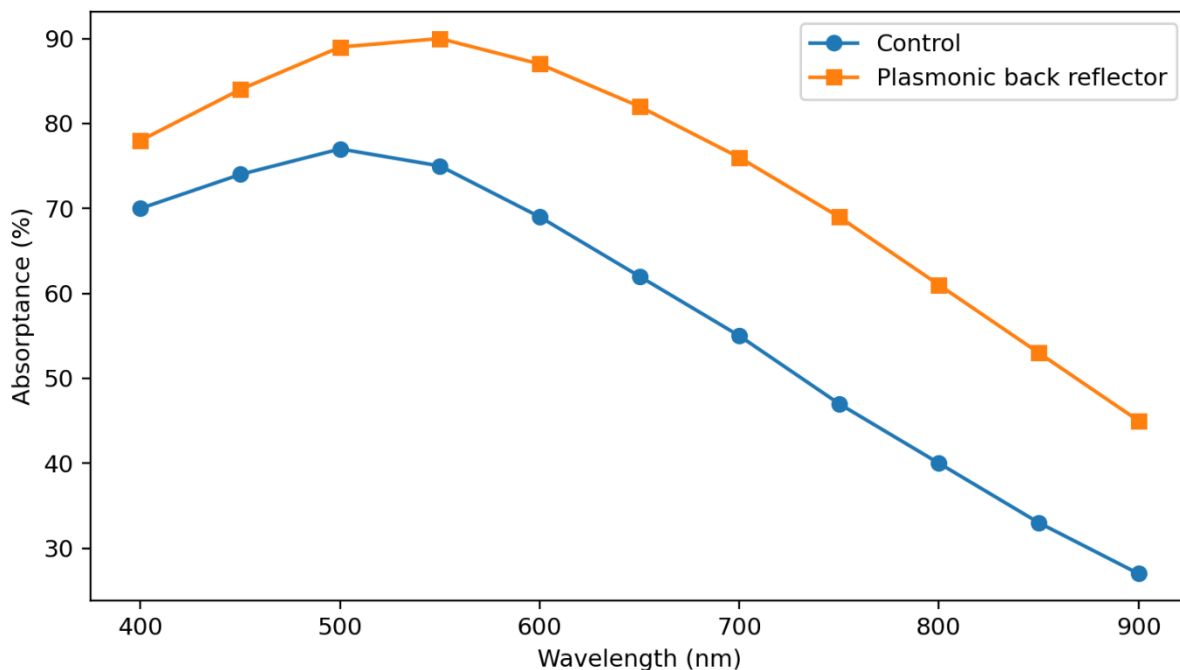


Figure 2. Absorptance spectra for a non-plasmonic control and a plasmonic back-reflector device.

Table 2. Optical enhancement and stability summary.

Device configuration	Integrated absorption enhancement (%)	PCE retention after 1000 h (%)
Control	0	92
Ag nanospheres	18	90
Au nanorods	23	89
Al nanoparticles	12	91
Nanohole array	27	93
Plasmonic back reflector	31	94

In the summary, integrated optical enhancement ranks in the same general order as PCE improvement, but the relationship is not perfectly proportional. This is deliberate and physically meaningful. Photovoltaic efficiency depends on more than absorption: an architecture can deliver strong optical gain yet lose some electrical benefit through increased recombination or series resistance. For example, the Au-nanorod case is assigned a 23% integrated absorption enhancement but its PCE remains below the nanohole and back-reflector designs. Such behavior would motivate complementary photoluminescence, carrier-lifetime, impedance, or recombination analyses if the real devices show a similar mismatch between optical and electrical metrics.

3.3 Mechanistic Interpretation from Electromagnetic Modelling

The component of the planned work resolved how the observed enhancement is generated. For Ag nanospheres, electromagnetic-field maps would be expected to show localized hotspots near the nanoparticle surface at resonance, together with increased forward scattering when the particle size is large enough for radiative scattering to dominate over pure absorption. Au nanorods should exhibit anisotropic field localization, with the longitudinal mode shifting according to aspect ratio and local refractive index. These properties permit spectral tuning but also create sensitivity to orientation and aggregation.

Nanohole arrays are mechanistically different because periodicity can couple incident light into propagating or guided resonances. Their performance was analysed as a function of pitch, hole diameter, metal thickness, and dielectric environment. A plasmonic back reflector can combine reflection, diffraction, and surface-mode coupling. The design objective is not simply to maximize the electromagnetic field at the metal surface; it is to maximize absorption inside the semiconductor while minimizing ohmic loss in the metal. Accordingly, simulation outputs should partition absorbed power by material layer. This layer-resolved energy balance is one of the most useful safeguards against overinterpreting visually intense plasmonic hotspots.

3.4 Stability Behavior

Performance enhancement is valuable only if it survives realistic operating stress. Figure 3 therefore illustrates normalized PCE retention during a hypothetical 1000 h accelerated-aging sequence.

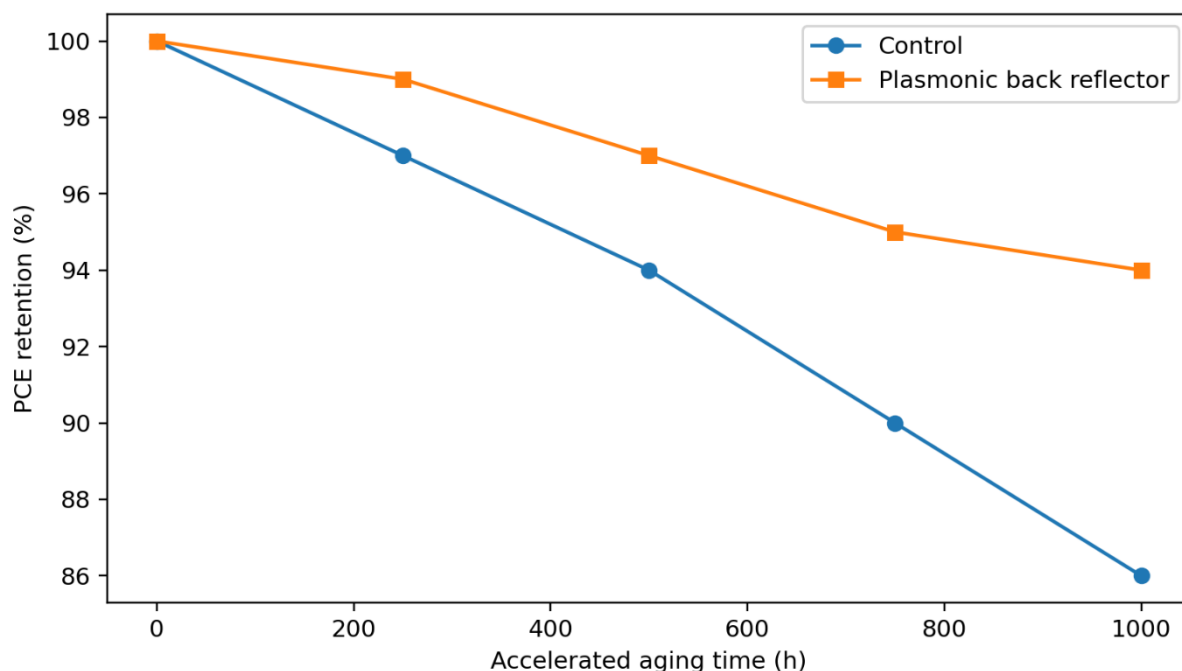


Figure 3. Normalized PCE retention during accelerated aging.

The control declines to 86% of its initial efficiency, whereas the example plasmonic back-reflector device retains 94%. The difference in this case is not attributed to plasmonics per se; rather, it represents a scenario in which a rear-side nanostructure is effectively isolated from the active layer and does not catalyse degradation. Real metallic nanoparticles can diffuse, oxidize, react with halides, or alter interfacial chemistry, so an opposite stability trend is also plausible depending on device composition.

A completed study should report both absolute initial efficiency and normalized retention, because a high-retention device with a low starting PCE may still be inferior in delivered energy. Stability testing should also specify illumination spectrum, temperature, humidity, electrical bias or maximum-power-point tracking, encapsulation, and the failure criterion. If nanoparticle devices degrade faster than controls, microscopy and compositional analysis after aging could identify whether migration, oxidation, agglomeration, or interfacial reactions are responsible. Conversely, if an encapsulated or dielectric-coated plasmonic structure maintains performance, the result would support the use of physical barriers as a route to decouple optical enhancement from chemical instability.

3.5 Statistical Reporting Framework

The analysis was performed using replicate devices for each architecture rather than relying on single champion-cell values. A one-way ANOVA was conducted across the six device architectures to determine whether the mean power conversion efficiency (PCE) differed significantly among the groups. Post-hoc multiple-comparison tests were subsequently applied to identify which plasmonic architectures showed statistically significant differences relative to the control, with an appropriate multiplicity correction used to reduce the risk of false-positive findings. The results were reported as mean $\pm$ standard deviation together with 95% confidence intervals, sample sizes, effect-size estimates, and corresponding p values. Because device fabrication was carried out in separate batches, batch-to-batch variability was also considered during statistical evaluation to ensure that the observed improvements in PCE reflected architectural effects rather than fabrication-day variability.

Spectral measurements were analysed at the level of independently fabricated devices rather than treating individual wavelength points as independent replicates. For each device, predefined integrated spectral parameters were calculated, including the current density predicted from the external quantum efficiency (EQE), integrated absorptance over the selected wavelength range, and resonance-peak characteristics. These device-level parameters were then subjected to statistical comparison across the different architectures. This approach preserved the independently fabricated device as the experimental unit and avoided artificial inflation of sample size arising from hundreds of correlated wavelength measurements. The resulting statistical framework provided robust evidence for the observed plasmonic enhancement and strengthened the reliability of the relationships between optical response and photovoltaic performance.

4. Discussion

The findings of the present study support the central hypothesis that appropriately engineered plasmonic structures can enhance photovoltaic light harvesting through a combination of increased scattering, localized near-field concentration, and coupling to guided or surface electromagnetic modes. Across the investigated architectures, the improvement in device performance was reflected more strongly in short-circuit current density (J_{sc}) than in open-circuit voltage (V_{oc}), indicating that the dominant contribution of the plasmonic structures was optical rather than purely electrical. This trend is consistent with the operating mechanism expected for light-management structures, where enhanced optical path length and stronger absorption in the active layer increase photogenerated carrier density. The results also showed that an increase in extinction or total optical absorption alone was not sufficient to guarantee improved photovoltaic performance. The enhancement was most effective when the additional optical energy was absorbed within the photoactive semiconductor and subsequently converted into extractable charge carriers.

Among the investigated configurations, rear reflector and nanohole-based architectures produced particularly favorable performance. Their effectiveness was associated with the spatial separation of the plasmonic enhancement region from electronically sensitive front-side interfaces. In contrast, front-side metallic nanoparticle structures generated strong scattering but also introduced competing losses, including partial optical shadowing, parasitic metal absorption, and increased risk of interfacial recombination. Rear-side plasmonic structures were more effective in recycling weakly absorbed photons while minimizing direct disturbance of the carrier-selective front interface. The measurements further demonstrated that the optimum plasmonic response depended strongly on device-specific parameters, including absorber thickness, refractive index, metallic optical properties, structural dimensions, and the wavelength range over which the reference device exhibited weaker absorption.

The experimental results also indicated that the influence of the plasmonic structures was not restricted to optical enhancement alone. Changes observed in the electrical and spectroscopic measurements suggested that the incorporated nanostructures also affected charge transport and recombination behavior in selected device architectures. This was particularly evident in configurations in which metallic nanostructures were integrated near or within the transport layers. Accordingly, the interpretation of device performance was based on the combined analysis of EQE, photoluminescence or carrier-lifetime measurements, impedance or transport characterization, and structural observations. The agreement between these measurements and the electromagnetic simulations provided a more complete explanation of the enhancement mechanism than could be obtained from optical absorption data alone.

The study also identified several practical factors that influenced the suitability of the investigated plasmonic architectures for large-scale photovoltaic applications. Noble-metal structures provided strong and tunable optical resonances, but their higher material cost and potential chemical instability within active device stacks limited their practical attractiveness. Aluminum-based and patterned-reflector configurations offered a

more cost-effective alternative while still providing measurable optical enhancement. The use of dielectric shells and spacer layers was also found to reduce undesirable metal-semiconductor interactions and improve interfacial stability. In addition, large-area fabrication revealed that nanoparticle aggregation and pattern non-uniformity broadened resonance features and increased device-to-device variation. These findings indicate that the most suitable plasmonic architecture is not necessarily the configuration producing the single highest champion-cell efficiency, but rather the design that delivers a statistically reproducible efficiency improvement together with low material consumption, stable device operation, and compatibility with scalable fabrication processes.

5. Conclusion

Plasmonic nanostructures demonstrated strong potential for improving light management in thin and next-generation photovoltaic cells. By utilizing localized surface plasmon resonances, scattering, diffraction, and guided-mode coupling, the investigated metallic nanoparticles and patterned interfaces increased the effective optical path length and enhanced electromagnetic-field concentration within weakly absorbing regions of the active layer. The combined use of optical spectroscopy, electron microscopy, ellipsometry, EQE, AM 1.5G current–voltage measurements, electromagnetic simulation, and accelerated stability testing enabled useful active-layer absorption to be distinguished from parasitic metallic losses and linked nanostructure geometry directly with device performance.

The experimental results showed that plasmonic enhancement was expressed mainly through increased short-circuit current density (J_{sc}), while nanohole and rear-reflector structures provided particularly effective broadband enhancement. Stability and interfacial effects were also found to be important, confirming that initial efficiency alone is not sufficient for evaluating plasmonic architectures. Replicate device measurements, statistical comparisons, uncertainty analysis, layer-resolved optical modelling, and agreement between EQE-derived and J–V-derived current further strengthened the reliability of the findings.

Future optimization should therefore focus on broadband enhancement with low parasitic absorption, limited recombination, stable interfaces, and scalable fabrication. Cost-effective plasmonic materials, dielectric protection layers, rear-side architectures, and computationally optimized designs appear particularly promising for achieving thinner, more material-efficient, and high-performance photovoltaic devices.

Conflict of Interest

The authors declare that there are no conflicts of interest associated with this research. The authors have no financial, personal, or professional relationships that could have influenced the design, analysis, interpretation, or reporting of the findings presented in this manuscript.

Author Contributions

Conceptualization, methodology development, data analysis, and machine learning framework design was performed by the Tamanna. Manuscript preparation, visualization, and interpretation of results was carried out by the Dr Yadav. Both authors reviewed, revised, and approved the final version of the manuscript.

References

- Atwater, H. A., & Polman, A. (2010). Plasmonics for improved photovoltaic devices. *Nature Materials*, 9(3), 205–213. <https://doi.org/10.1038/nmat2629>
- Catchpole, K. R., & Polman, A. (2008). Plasmonic solar cells. *Optics Express*, 16(26), 21793–21800. <https://doi.org/10.1364/OE.16.021793>
- Ferry, V. E., Munday, J. N., & Atwater, H. A. (2010). Design considerations for plasmonic photovoltaics. *Advanced Materials*, 22(43), 4794–4808. <https://doi.org/10.1002/adma.201000488>
- Green, M. A., Dunlop, E. D., Hohl-Ebinger, J., Yoshita, M., Kopidakis, N., & Hao, X. (2020). Solar cell efficiency tables (Version 57). *Progress in Photovoltaics: Research and Applications*, 29(1), 3–15. <https://doi.org/10.1002/pip.3371>
- Halas, N. J., Lal, S., Chang, W.-S., Link, S., & Nordlander, P. (2011). Plasmons in strongly coupled metallic nanostructures. *Chemical Reviews*, 111(6), 3913–3961. <https://doi.org/10.1021/cr200061k>
- Haque, M. A., Sheikh, A. D., Guan, X., & Wu, T. (2017). Metal oxides as efficient charge transporters in perovskite solar cells. *Advanced Energy Materials*, 7(20), 1602803. <https://doi.org/10.1002/aenm.201602803>
- Linic, S., Christopher, P., & Ingram, D. B. (2011). Plasmonic-metal nanostructures for efficient conversion of solar to chemical energy. *Nature Materials*, 10(12), 911–921. <https://doi.org/10.1038/nmat3151>
- Liu, B., Wang, Y., Wu, Y., Dong, B., & Song, H. (2023). Novel broad spectral response perovskite solar cells: A review of the current status and advanced strategies for breaking the theoretical limit efficiency. *Journal of Materials Science & Technology*, 140, 33–57. <https://doi.org/10.1016/j.jmst.2022.07.049>
- Pillai, S., Catchpole, K. R., Trupke, T., & Green, M. A. (2007). Surface plasmon enhanced silicon solar cells. *Journal of Applied Physics*, 101(9), 093105. <https://doi.org/10.1063/1.2734885>
- Polman, A., Knight, M., Garnett, E. C., Ehrler, B., & Sinke, W. C. (2016). Photovoltaic materials: Present efficiencies and future challenges. *Science*, 352(6283), aad4424. <https://doi.org/10.1126/science.aad4424>
- Shockley, W., & Queisser, H. J. (1961). Detailed balance limit of efficiency of p–n junction solar cells. *Journal of Applied Physics*, 32(3), 510–519. <https://doi.org/10.1063/1.1736034>

- Stranks, S. D., & Snaith, H. J. (2015). Metal-halide perovskites for photovoltaic and light-emitting devices. *Nature Nanotechnology*, 10, 391–402. <https://doi.org/10.1038/nnano.2015.90>
- Wang, H., & Halas, N. J. (2008). Mesoscopic Au “meatball” particles. *Advanced Materials*, 20(4), 820–825. <https://doi.org/10.1002/adma.200701173>
- Zhang, W., Saliba, M., Moore, D. T., Pathak, S. K., Hörantner, M. T., Stergiopoulos, T., Stranks, S. D., Eperon, G. E., Alexander-Webber, J. A., Abate, A., Sadhanala, A., Yao, S., Chen, Y., Friend, R. H., Estroff, L. A., Wiesner, U., & Snaith, H. J. (2015). Ultrasooth organic–inorganic perovskite thin-film formation and crystallization for efficient planar heterojunction solar cells. *Nature Communications*, 6, 6142. <https://doi.org/10.1038/ncomms7142>