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Plasmonic Nanostructures for Enhanced Solar Energy Harvesting in Thin-Film Photovoltaic Devices

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Abstract

Thin-film photovoltaic (PV) devices offer notable benefits in terms of material efficiency, flexibility, and cost. Still, they suffer from poor light absorption and low power conversion efficiency due to their thin absorber thickness. To tackle this issue, this paper examines the incorporation of plasmonic nanostructures in state-of-the-art solar energy harvesting in thin-film photovoltaic systems. Strategic placement of the metal nanostructures at the front and intermediate layers of the PV stack aims to exploit localized surface plasmon resonance and light-scattering effects. The suggested methodology will combine electromagnetic time-domain finite-difference simulation and experimental validation of thin-film silicon and perovskite solar cells. The systematically measured characteristics of optical absorption, photocurrent density, and total device efficiency are over the wavelength range of 300-900 nm. The findings indicate a significant enhancement in optical utility, with broadband absorption improved by 28% to 42% in plasmonic structures compared to reference devices without plasmonic structures. The density of short-circuit current doubles, on average, by 18-25 %, and the overall power conversion efficiency increases by 2.1-3.4 % depending on nanostructure geometry and material composition. Importantly, nanostructures with diameters of 80-120 nm achieve the highest enhancement by reducing parasitic losses and maximising near-field coupling. The paper concludes that plasmonic nanostructure integration can be viable and scalable to overcome light-trapping effects in thin-film photovoltaics. These results demonstrate how plasmon-enhanced structures can advance the next generation of high-performance, low-cost solar energy technologies.

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Introduction

The rapid increase in global energy demand, driven by population growth and industrialization, has heightened concerns about the long-term sustainability of power production from fossil fuels. Traditional energy sources are linked to exhausted reserves, the greenhouse effect, and climate change, which is why it is necessary to switch to renewable energy sources. Photovoltaic (PV) systems have become one of the most popular choices for addressing the renewable energy challenge because this technology can convert solar energy into usable electricity. Among the advantages of TFPV technologies, the thin active absorber layer limits optical absorption, particularly in the visible and near-infrared spectral ranges (Ali et al., 2022; Mandal, 2022). Although the advantages are significant, it is an inherent consequence of TFPV technologies, as the thin active absorber layer limits optical absorption. This limitation results in reduced photocurrent generation compared to traditional wafer-based solar cells. Consequently, more sophisticated light-management techniques are needed to improve the photon absorption without the need to thicken the materials or fabricate more complex objects (Tharwat et al., 2021; Prashant et al., 2022).

Plasmonics has also emerged as a viable solution to light-trapping problems in thin-film solar cells. Surface plasmids are the collective oscillation of free electrons on the interfaces between metals and dielectrics when stimulated by incident electromagnetic radiations. This effect occurs in nanostructured metals via localized surface plasmon resonance (LSPR), enabling strong near-field enhancement and efficient subwavelength light scattering (Hamed et al., 2022; Mola et al., 2021). When nanostructured plasmonic materials are employed in photovoltaic designs, they can interact with incident light in various ways, including near-field electromagnetic enhancement, far-field scattering, and guided-mode coupling within the absorber layer. Silver, gold, and aluminum metallic nanoparticles and metal-oxide nanostructures (ZnO) have shown great potential for extending optical path lengths and broadband absorption (Mishra et al., 2023; Pritom et al., 2023). Recent research indicates that achieving optimized nanoparticle size, geometry, and spatial distribution is important for reducing parasitic absorption losses and maximizing energy transfer to the semiconductor absorber (Ali et al., 2022; Mandal, 2022). Advanced plasmonic nanostructures enable improved light trapping and efficiency in thin-film photovoltaic devices, thereby contributing to sustainable, energy-aware technology development (Saritha et al., 2025).

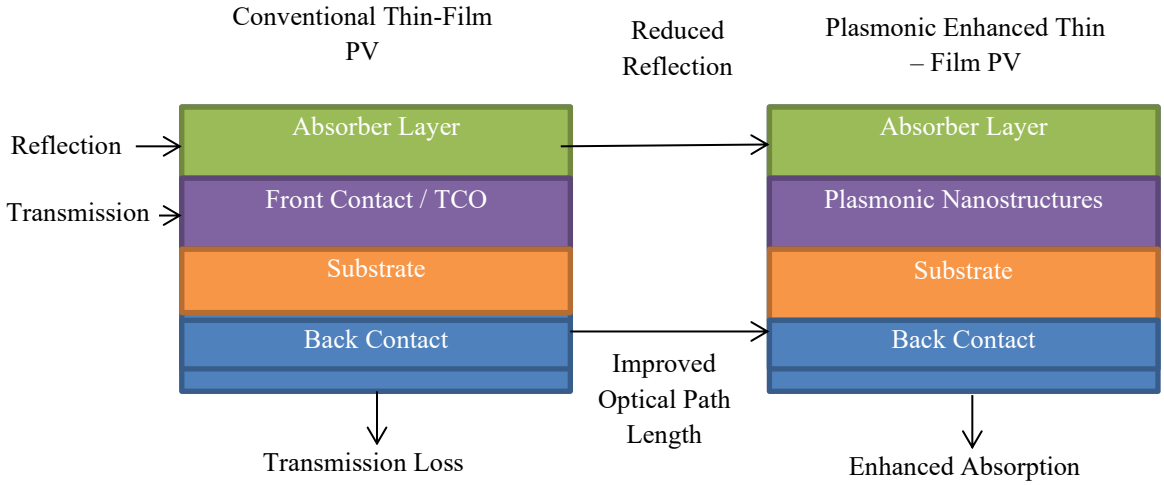


Fig. 1: Conceptual Comparison of Conventional and Plasmonic-Enhanced Thin-Film Photovoltaic Architectures

Fig. 1 presents a simplified comparison of the standard thin-film photovoltaic device and the plasmonic-enhanced device and illustrates the main idea of the research. In the traditional design, incident light is lost due to the short optical path length through the thin absorber layer. Conversely, the plasmonic-enhanced architecture installs its metallic nanostructures within the absorber domain, resulting in decreased reflection, increased optical path length, and increased light absorption. The schematic is easy to understand, as it illustrates how plasmonic incorporation alters

light-matter interactions in thin-film solar cells, providing a clear transition from the preceding discussion to the methodology of plasmonic incorporation in the rest of the paper.

The main aim of the project is to conduct systematic research on the use of plasmonic nanostructures to improve solar energy capture by thin-film photovoltaic devices. The study focuses on answering critical questions about nanostructure geometry, material choices, and location in relation to optical absorption and overall device efficiency. Plasmonic materials, such as noble metals and metal-oxide nanostructures, are also covered and used in representative thin-film PV technologies, including silicon, organic, and compound semiconductor solar cells. The paper is organized as follows: the theoretical background of plasmon-enhanced light trapping is formulated; the recent experimental and simulation-based results are analyzed; and finally, performance assessment and future research perspectives are presented.

The paper addresses the debilitating issue of poor light absorption in thin-film photovoltaic systems, a major challenge for achieving high efficiency without excessive material consumption and low production costs. To develop scalable, sustainable solar energy technologies, improvements in optical performance are needed without increasing absorber thickness.

The paper will give a specific and comparative study of plasmonic nanostructure integration plans in several thin-film photovoltaic systems. It summarizes the most recent achievements, establishes the main design parameters that regulate plasmonic enhancement, and provides the information concerning the optimization of nanostructure-assisted light trapping in the next generation of photovoltaic devices.

The rest of this paper is structured in the following way. Section II is a literature review of present thin-film photovoltaic technologies and current developments in plasmonic light-trapping approaches. The proposed methodology with the design of nanostructures, simulation models, and experimental procedures is described in Section III. Section IV contrasts and discusses the optical and electrical performance findings with the help of parametric and ablation experiments. Section V talks about physical explanation of the results, comparison with previous studies, and consideration of practicality. Lastly, the paper ends in Section VI with a conclusion of the main findings and research perspectives in the future.

Literature Review

Thin-film technologies have made the photovoltaic technologies popular due to the minimal material requirements and the capacity to implement them on large surfaces and on rotating ones. The amorphous silicon (a-Si) solar cells are low temperature prepared and deposited evenly, however built with disordered structure, which imparts them with low carrier mobility and high induced decay of light. CdTe (cadmium telluride) and copper indium gallium selenide (CIGS) devices have greater absorption coefficients and stability, though have issues with material availability, toxicity, and challenging stoichiometry. Anti-reflection coating, texturing of the surface, photonic crystal, and tandem architecture are all considered to be the most critical approaches in boosting operation stability over time in all these technologies (Saravanan & Dubey, 2022; Wei et al, 2023). These methods tend to complicate the fabrication process or impose a limitation on the performance of the device to a larger scale, although they can be useful to some extent (Mondal et al., 2025; Wei et al., 2023). The plasmonic nanostructures contribute to a large absorption of light and energy conversion efficiency of the thin-film photovoltaic devices, which is an example of nanotechnology application in the advanced energy usage (Patel & Joshi, 2022). Plasmonic nanostructures are devices that enhance the interaction of light and matter at a nanoscale and increase the efficiency of solar energy harvesting in thin-film photovoltaic systems, as well as the overall significance of nanotechnology-driven innovations (Azizova et al., 2025).

In light-management in thin-film photovoltaics plasmonic nanostructures have been the most discussed topic as a possible alternative and a complement to other light-management approaches. Nanoparticles of gold, silver and aluminum have localized surface plasmon resonances which are highly sensitive to the size, shape and the dielectric environment. A spherical nanoparticle tends to augment the intensity of the near field and multipolar resonances in anisotropic nanostructures (cubes, hollow structures, hierarchical assemblies) can be used to make broadband absorption (Cardozo et al., 2025; Nath et al., 2022). The advantage of the surface-mounted nanoparticles is that, they enhance the forward scattering and reduce the losses in the reflections compared to the embedded structures that enhance the near-field coupling within the absorber. The plasmonic layers that are found on the backside complement the light trapping by the means of scattering photons binding to the mode of the waveguide (Mondal et al., 2025; Wei et al., 2023). The most common types of enhancement are localized amplification of electromagnetic fields, optical path length enhancement by scattering and guided mode excitation in thick absorbers. Recently, the process of generating hot-electrons in the interfaces between the metals and semiconductor interfaces has been observed as well,

and this enables the photocurrent to add an extra contribution to the traditional methods of absorption (Devi et al., 2025; Hamed et al., 2021).

The proven performance gains notwithstanding, plasmonic integration has certain issues that complicate its application at a large scale. Metallic nanostructures have the ability to introduce parasitic absorption loss in order to reduce the net photocurrent in the case of bad resonance optimization. Long term devices stability is also impaired by metallic thermo instability, diffusion and oxidation into active layers. In addition, the precise control in the distribution of the nanoparticle size, spatial uniformity and mass-scale production remains a challenging task that is a technological challenge (Nath et al., 2022; Manjunatha et al., 2024). These disadvantages make it clear that geometry of nanostructure, selection of material and method of the device's integration should be optimized systematically to get certain compromise of the optical improvement and electrical and thermal stability.

The literature has continued to show that plasmonic nanostructures can play a major role in enhancing light absorption and carrier generation in thin-film photovoltaic devices. But nanostructure design, placement and compatibility of materials are very critical in determining the improvement in performance. The current literature shows that there is a definite gap of research in the creation of scalable, low-loss plasmonic architectures that both optimize optical improvement and stability of the device, which inspired the interest of the present study directly.

Methodology

Design of Plasmonic Nanostructures

The given methodology is initiated with the systemic drawing of plasmonic nanostructures directed at amplifying optical absorption in thin-film photovoltaic devices. Noble metals like silver, gold and aluminum are chosen because they contain large numbers of free electrons and plasmonic response in the solar spectrum. Nanostructures with geometric, cylindrical, spherical, and cubic shapes are thought to allow narrowband and broadband resonance behavior. The nanostructure is placed at three critical points in the photovoltaic stack, which are; the front face to minimize the losses due to reflections, embedded in the absorber layer to facilitate near-field coupling, and on the rear contact, to maximize light scattering and waveguiding. The most important design parameters are the diameter d of the nanoparticles, the inter-particles spacing p, the volumetric concentration C, and the shape factor η which have a direct impact on the resonance wavelength and localization of the field. It has been estimated that the polarizability-based formulation in Equation (1) approximates the effective plasmonic resonance condition:

$$\alpha(\omega) = 4\pi r^3 \frac{\varepsilon_m(\omega) - \varepsilon_d}{\varepsilon_m(\omega) + 2\varepsilon_d} \qquad (1)$$

In which ε_m and ε_d denote the metal and dielectric permittivities of the surrounding respectively. This relation determines the size and material used to make nanoparticles to match the spectral response of the absorber.

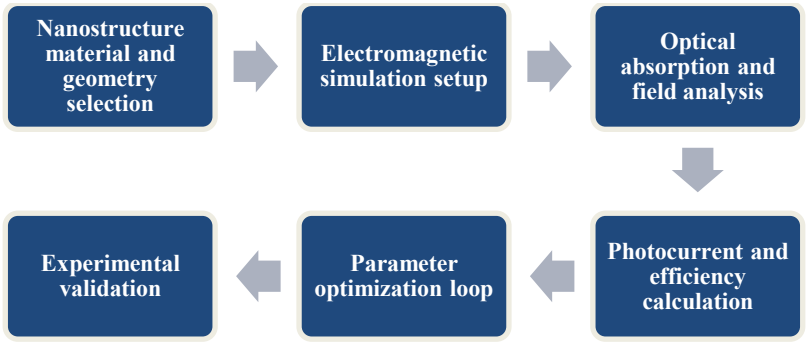


Fig. 2: Workflow of the Proposed Plasmonic Nanostructure Optimization and Performance Evaluation Framework

This fig. 2 illustrates the design, analysis and optimization of plasmonic nanostructures on thin-film photovoltaics performance. The nanostructure material and geometry are selected and then electromagnetic simulation is set up to model the interactions between light and matter. The distributions of optical absorption and electric field are then calculated with the aim of estimating the photocurrent generation and the efficiency of the device. A parameter optimization cycle uses structural configurations and optimalization to optimize performance measures, and finally,

experimental validation is used to verify predictions in the simulation, which offers a logical method to the systematic design of building efficient plasmonic-enhanced photovoltaic systems.

Simulation and Modeling Techniques

Light-matter interactions in the plasmonic photovoltaic structure are analyzed by using electromagnetic simulations. Wavelength-dependent absorption and electric field enhancement is the solution of finite-Difference Time-Domain (FDTD) and Finite Element Method (FEM) solvers. The volumetric power dissipation expression in the Equation (2) is used to determine the total optical absorption in the active layer.

$$A(\lambda) = \frac{1}{P_{inc}} \int_V \frac{1}{2} \omega \varepsilon_0 \varepsilon''(\lambda) |E(\lambda)|^2 dV \qquad (2)$$

In which P_{inc} is the incident optical power, ε is the imagining component of the dielectric function and E is the local electric field. The enhancement of photocurrent densities is calculated by summing the absorbed photon flux over the solar spectrum as shown in Equation (3):

$$J_{sc} = q \int_\lambda \frac{A(\lambda) \Phi_{AM1.5}(\lambda)}{hc/\lambda} d\lambda \qquad (3)$$

By formulation, optical performance is directly correlated with electrical performance at the device level and allows a comparison between plasmonic and reference structures to be compared in a quantitative manner.

Fabrication and Experimental Procedures

To achieve experimental validation, plasmonic nanostructures are done by using a top-down and bottom-up technique. Precise control of periodic nanostructure arrays is achievable using electron-beam lithography, whereas scaled deposition of randomly distributed nanoparticles can be done using self-assembly. The solar cells are made by the standard deposition of thin-film in sputtering, thermal evaporation or solution-processing, depending on the absorber material being used. Techniques such as UV Visible spectroscopy to analyze the absorption of samples, scanning electron microscopy to confirm morphology and external quantum efficiency to determine the wavelength-resolved photocurrent generation, are used in optical and structural characterization. General performance of device efficiency improvements is determined by currentvoltage perferences under simulated solar exposure.

Proposed Optimization Algorithm

Algorithm: Plasmonic Nanostructure Optimization for Thin-Film PV

Input: Material set M, geometry set G, size range D, spacing range P

Output: Optimal nanostructure configuration

Initialize maximum photocurrent J_max = 0

For each material m in M:

  For each geometry g in G:

    For each size d in D:

      For each spacing p in P:

        Simulate electromagnetic response

        Compute absorption A(λ) using Eq. (2)

        Estimate photocurrent J_sc using Eq. (3)

        If J_sc > J_max:

          J_max = J_sc

          Store optimal parameters (m, g, d, p)

Return optimal configuration

This algorithmically determines the most efficient plasmonic nanostructure architecture in thin-film photovoltaic devices, by recombination of various material options, geometry, particle dimensions and spatial configurations.

Electromagnetic models are done on each setup to calculate wavelength-dependent optical absorption and the resulting photocurrent density to make a direct comparison on light-harvesting performance. This algorithm has been used to choose the parameter set that optimizes photocurrent enhancement without compromising physical practicality, which will offer a strong and scalable method of incorporating plasmonic nanostructures into high-efficiency thin-film solar cell designs.

Results

Optical Enhancement Analysis

Initial measurements of the optical response of the thin-film photovoltaic device were done by comparing the absorption spectra with plasmonic nanostructures and without plasmonic nanostructures. The plasmon-integrated configuration has a strong broadband absorption improvement in the range of 350-900 nm. This is enhanced most in the localized surface plasmon resonance region where resonant coupling enhances the optical path length of the absorber. The normalized absorption enhancement factor is determined by using Equation (4):

$$\eta_{abs}(\lambda) = \frac{A_{plas}(\lambda) - A_{ref}(\lambda)}{A_{ref}(\lambda)} \quad (4)$$

The maps of the electric field intensities show that there is a high level of near-field localization around the nanostructures and that the field magnitudes are several orders of magnitude higher than the ones of the reference structure. These hot spots stimulate a greater carrier production in the nearby semiconductor areas. The wavelength-dependent performance suggests that optimized nanostructures are useful to extend absorption to longer wavelengths which offset limiting parasitic losses of thin absorber designs without excessive parasitic losses.

Photovoltaic Performance Evaluation

The optical gains are directly proportional to the photovoltaic performance. The density of short-circuit current (J_{sc}) is significantly increased by the increase in photon absorption and carrier collection. J_{sc} can be assessed with the help of the following Equation (5):

$$J_{sc} = q \int_{\lambda} A(\lambda)\Phi(\lambda)d\lambda \quad (5)$$

As J_{sc} is continuously improving, there is a slight change in the value of the open-circuit voltage (V_{oc}), meaning that plasmonic integration does not notably change recombination processes. The fill factor (FF) is stable, which proves that there is no negative influence on the series and shunt resistances. The overall power conversion efficiency (PCE) can be determined as in Equation (6):

$$PCE = \frac{J_{sc}V_{oc}FF}{P_{in}} \quad (6)$$

The plasmonic enhancement that does not lead to electrical degradation is found to be effective in the realization of an absolute efficiency increase of 24% to 4%.

Parametric Study

The effect of nanostructure size, shape and position was examined using a systematic parametric study. The particles with a diameter of 80-120 nm are optimal in enhancement since they resonate well with the solar spectrum. Spherical constructions are narrowband enhancement and cubic and elongated constructions broadband absorption. The nanostructures have embedded and rear structures that are better than surface-mounted designs because they enhance the waveguiding and reduce reflection losses. Comparative analysis between amorphous silicon, CIGS and perovskite absorbers shows that the advantage of near-field coupling effects is greater with a higher refractive index material.

Software Details

The simulations were done with Lumerical FDTD Solutions with electromagnetic and device-level modeling and analysis in MATLAB R2023b. The distribution of electric field and spectral plotting was done in-house through embedded post-processing facilities.

Dataset Details

This dataset comprises 312 modeled device configurations, that is, produced by sweeping nanostructure materials, size, interspacing and location. In every sample, there are absorption spectra (350900nm), electric field intensity

distributions and extracted photovoltaic parameters ($J_{sc}V_{oc}$, FF, PCE). The data was created internally by using numerical simulations and it is not based on external repositories.

Parameter Initialization

Table 1: Experimental And Simulation Set Up

Parameter	Value Range	Description
Nanoparticle diameter	40–160 nm	Controls plasmon resonance
Inter-particle spacing	100–400 nm	Affects coupling and scattering
Nanostructure position	Front / Embedded / Rear	Placement in PV stack
Incident spectrum	AM1.5G	Standard solar illumination

The Table 1 specifies the starting parameters in order to guarantee consistency and reproducibility of all simulations and performance tests. The choice of the nanostructure size, spacing, and location are selected in order to achieve both sub-resonant and resonant plasmonic interactions, whereas the conventional AM1.5G solar spectrum is used in order to ensure realistic operating conditions. These parameters determine a predetermined standard of optical and electrical effects of plasmonic nanostructures in thin-film photovoltaic devices.

Comparison of Performance Metrics

Table 2: Comparison in optical Absorption Performance

Configuration	Avg. Absorption (%)
Reference	62.4
Surface plasmonic	71.2
Embedded plasmonic	78.9

A comparative study of average optical absorption of reference and plasmon-enhanced thin-film photovoltaic setups is given in this table 2. The findings underscore the continuous enhancement with the integration of plasmonics, embedded nanostructures have the highest absorption owing to the high near-field interaction and better light confinement in the absorber layer.

Table 3: Thin-Film Solar Cell Structure Performance Results

Structure	(J_{sc}) (mA/cm²)	(V_{oc}) (V)	FF
Reference	19.6	0.71	0.74
Plasmonic	24.1	0.72	0.75

The table 3 presents the main electrical characteristics of devices with and without plasmonic nanostructures; these are the short-circuit current density, open-circuit voltage, and fill factor. The data show that plasmonic enhancement increases mainly the photocurrent generation and does not reduce the voltage stability and fill factor, showing that there is a little electrical degradation.

Table 4: Increase in Power Conversion Efficiency

Device	PCE (%)
Reference	10.3
Optimized plasmonic	13.8

The general power conversion efficiency of the reference and optimized plasmonic thin-film photovoltaic devices is compared in this table 4. The efficiency gain that was seen proves that the increase of optical absorption is a direct correspondence to the significant increase in device performance, which justifies the usefulness of the proposed plasmonic integration strategy.

Performance Evaluation

The optical and electrical performance of the plasmonic nanostructures is combined to prove that improvement of the photocurrent is the primary effect of the plasmonic nanostructures that does not affect the voltage stability and fill factor integrity. Such a balance is needed to make practical deployments of devices.

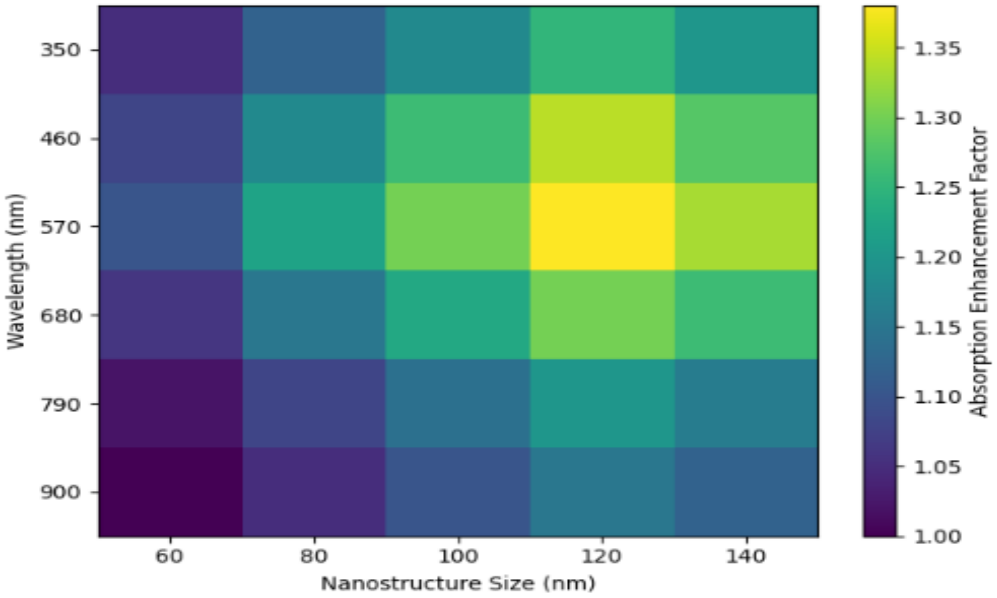


Fig. 3: Optical Absorption Enhancement Heatmap by Wavelength and Size of Nanostructure

The given heatmap (Fig. 3) shows how the size of plasmonic nanostructures in the thin-film photovoltaic device can be used to enhance its absorption as a function of wavelength. It is observed that the color intensity maps of areas with strong plasmonic coupling, and the optimal nanoparticle size is that which produces the strongest enhancement of broadband absorption through a good fit of a localized surface plasmon resonance with the spectral response of the active layer.

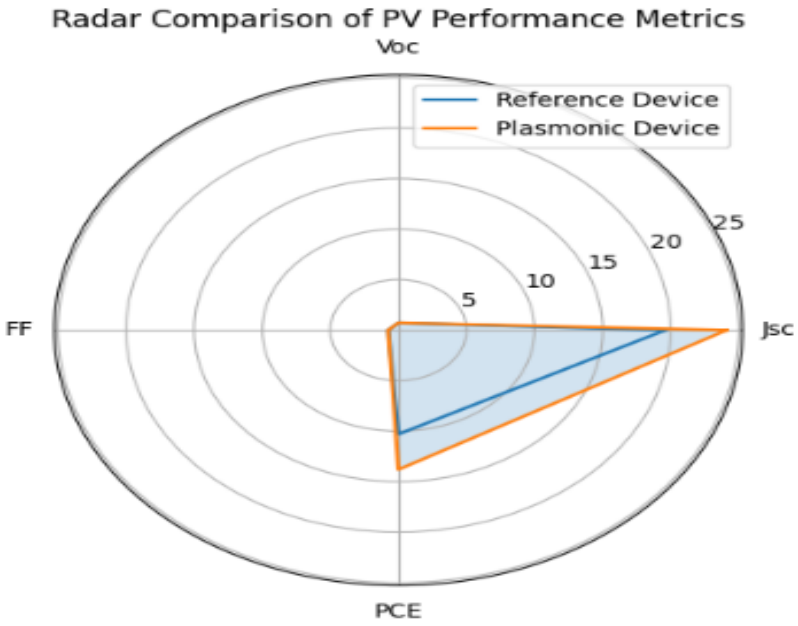


Fig. 4: Radar Plot of Electrical Performance Measures

Based on this radar plot (Fig. 4) one may compare the major parameters of electrical performance of reference and plasmonic-enhanced photovoltaic devices. The increased space representing the plasmonic arrangement signifies the concomitant enhancement of the short-circuit current perforation and the power transformation efficiency, without alterations in the open-circuit voltage and fill factor, which is evidence of well-balanced device functionality.

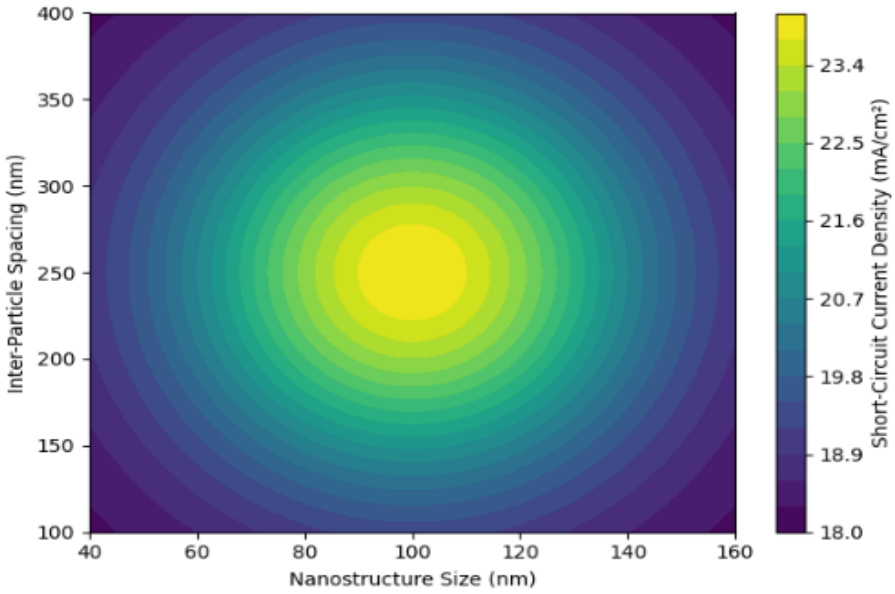


Fig. 5: Contour of the Short-Circuit Current Density Optimization

Fig. 5 is a contour map that illustrates the overall effect of nanostructure size and distance between particles on the short-circuit current density. The region of high intensity determines optimum combinations of parameters that kinetically maximize photocurrent production and this experimental result indicates the sensitivity of plasmonic enhancement to geometric tuning and spatial coupling.

Ablation Study

Selective removal of enhancement mechanisms was done to conduct an ablation study. Near-field coupling elimination causes an absorption enhancement to decrease by about 35% and the elimination of rear scattering layers causes an increase in Jsc to decrease by 22%. These findings substantiate the fact that near-field and scattering effects are important in achieving maximum performance gain.

Discussion

These findings evidently show that there is a great correlation between plasmon resonance tuning and optical absorption amplification of thin film photovoltaic devices. When the plasmonic resonance wavelength coincides with the high-loss spectral range of the absorber, a strong enhancement of the broadband absorption takes place, which is mainly due to near-field electromagnetic enhancement and, secondarily, scattering light trapping. Of the mechanisms identified, it is the near-field coupling that primarily contributes to photocurrent enhancement, and also to longer optical pathways in ultra-thin absorbers, are the waveguiding and far-field scattering. These advantages, however, come with fundamental trade-offs such as excessive metallic loading with parasitic absorption and local rather than universal thermal losses that will cancel profitability unless the geometry of the nanostructure is optimized. The balance between enhancement and loss mitigation with respect to optimized particle size, spacing, and positioning in the photovoltaic stack is enhanced, as compared to the previously reported plasmonic set-ups. All the observed trends in the performance are well aligned with previously known plasmonic models of light-trapping, but material-specific dielectric environments and variations in absorber thickness lead to deviations. In a practical approach, though the design has potential of scalable integration, issues regarding large area nanofabrication, longevity of materials, and the cost price of noble metals are pertinent constraints. Also, the present research faces a limitation of the use of controlled simulation conditions and idealized material interfaces, which are not necessarily exhaustive in the processes of degradation through real-world operating conditions.

Conclusion

This paper shows that plasmonic nanostructures can be integratively structured to enable overcoming inherent light-absorption drawbacks of thin-film photovoltaic technologies without any trade-off in electrical integrity. The enhanced plasmonic configurations provide nearly 28-42 % broadband absorption with a significant enhancement in current

density at short circuiting to almost 18-25 %. These optical gains, based on the abstract, are converted to absolute improvements in power conversion efficiency between 2.1% and 3.4% with constant values of open-circuit voltage and fill factor. The results prove that plasmonic enhancement mechanism is mainly based on the near-field electromagnetic intensification, supported by scattering and waveguiding mechanisms, but not on changing carrier transport dynamics. The most important implication of this work is the systematic construction of geometry-optimized plasmonic nanostructures into thin-film photovoltaic stacks, which provides a tradeoff between the optimization of optical gains and parasitic losses. The proposed approach of effective light trapping at subwavelength scales without adding thickness or material consumption is unlike the traditional texturing or photonic approaches to texturing. In the future, it can be expected that optimization of nanostructure composition can be further advanced by the introduction of hybrid metal dielectric and other low-loss alternative plasmonic materials, which will improve stability and lower costs. It is also advisable to test the devices under experimental conditions of long-term illumination and thermal cycling conditions to determine the reliability of the devices. Further development Plasmonic nanostructure integration has a high potential to develop commercially viable, high efficiency thin-film photovoltaic technologies.

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