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Plasmonic Nanoparticles for Solar Cells: A Survey

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Abstract- Plasmonic nanoparticles are a powerful way to improve the performance of modern solar cells by changing how light works at the nanoscale. The LSPRs enabled these nanoparticles to trap light more efficiently, amplify near-field interactions, and produce energetic hot carriers that may be used for photocurrent enhancement. This review provides a comprehensive overview of the underlying physical mechanisms, the material choices, the geometries of nanoparticles, the approaches for device integration, and the modelling techniques concerning plasmonic-enhanced photovoltaic systems. More emphasis will be given to advances both in theoretical understanding and in experimental demonstrations across silicon, organic, perovskite, and dye-sensitized solar cells. Additionally, the review explains how scientists are employing simulations and computational tools to enhance nanoparticle placement, reduce parasitic losses, and forecast optical–electrical behavior. Despite the progress made, challenges remain. These include material stability, thermal effects, recombination losses, and scaling up fabrication. The survey wraps up by discussing future research directions and new opportunities in plasmonic photovoltaics, especially focusing on next-generation materials, hybrid photonic–plasmonic structures, and better hot-carrier extraction methods.

Keywords: “Modelling, LSPR, perovskite, solar cells, light trapping, plasmonics, nanoparticles”.

I. INTRODUCTION

The rapid growth of global electricity demand, together with the urgent need to decrease energy dependence on fossil fuels, drives the scientific and technological development toward further efficiency enhancements of PV systems. Silicon-based solar cells dominate current implementations because of their maturity and reliability; however, the Shockley–Queisser efficiency limit, combined with material constraints, has been a driving force for the development of advanced light-management strategies [1], [2].

Traditional approaches to light trapping have reached practical limits, such as surface texturing, anti-reflection coatings, and dielectric multilayers, particularly for emerging thin-film solar technologies where the absorber layers are merely several hundred nanometers thick [3], [4]. This has led to the emergence of plasmonic nanophotonics as one promising route beyond conventional optical confinement methods. Plasmonic nanoparticles, which are usually made of precious metals like gold (Au) and silver (Ag), support LSPRs, which allow light and matter to interact in new ways at the nanoscale [2], [6]. When these nanoparticles are lit up, the free electrons inside them move together, which makes the near-field stronger, the scattering stronger, and the absorption more selective for certain wavelengths. These properties can notably enhance the effective optical path length within solar absorbers, hence enhancing photon-to-electron conversion even in ultrathin devices [4], [7]. Besides classical light trapping, the decay of plasmonic excitations may also generate hot carriers - energetic electrons and holes that offer pathways toward exceeding conventional PV efficiency limits [8], [11].

Indeed, the incorporation of plasmonic nanostructures has been successfully demonstrated on a wide variety of photovoltaic platforms, including crystalline silicon solar cells [3], thin-film amorphous silicon cells [4], organic photovoltaics [18], dye-sensitized solar cells [18], and, more recently, highly efficient perovskite solar cells [12], [17]. In the case of perovskites, besides enhancing optical absorption, plasmonic nanoparticles influence crystallization dynamics, defect passivation, and charge transport—offering dual benefits both at the optical and material levels [12], [17]. Similarly, organic solar cells have used plasmonic effects in attempts to overcome exciton diffusion limitations and broaden the absorption spectrum [18]. In conjunction with the experimental developments, computational modeling has become an integral part of understanding and designing plasmonic-PV systems. Numerical solvers like COMSOL Multiphysics (FEM) and Lumerical FDTD Solutions allow for detailed insight into electromagnetic field distributions, the scattering behavior, and the coupled optical-electrical performance [9], [10].

Analytical models based on Mie theory provide a theoretical foundation for the nanoparticle scattering and absorption phenomena [10]; recently, machine-learning-assisted optimization has also been emerging as one of the powerful tools for optimizing nanoparticle geometry and array design [24]. Besides these developments, there are a number of issues that seriously prevent commercialization of plasmonically enhanced solar cells on an industrial scale. Among them are metal oxidation, especially for Ag; thermal instabilities; parasitic ohmic losses; interfacial recombination; and finally the challenge to obtain uniform nanoparticle depositions on large areas [7], [14], [16].

Moreover, successful engineering needs to be performed to balance plasmonic benefits with the risk of the introduction of additional recombination pathways. Given such rapid growth in research in this area, there is an urgent need for a comprehensive survey that ties together the theoretical underpinnings, the different material options and nanoparticle geometries, the various integration strategies, modelling techniques, and practical challenges involved. This review aims to fill these gaps by providing a systematic overview of photovoltaic enhancement using plasmonic nanoparticles. State-of-the-art established plasmonic mechanisms are discussed along with the most recent approaches: hybrid photonic-plasmonic structures, low-loss alternative materials like TiN [22], and advanced hot-carrier extraction techniques [8], [11]. Finally, emerging opportunities for the integration of plasmonics on next-generation PV platforms are discussed, with emphasis on scalable fabrication and performance optimization.

II. PHYSICAL MECHANISMS IN PLASMONIC PHOTOVOLTAICS

- **Localized Surface Plasmon Resonance (LSPR)**

LSPR arises due to collective oscillation of conduction electrons in metallic nanoparticles that results in resonant absorption together with strong localization of the field [2], [6], [10]. Resonant frequency depends on nanoparticle shape, material, and also on the dielectric surroundings [6].

- **iScattering and Far-Field Light Trapping**

Metallic nanoparticles larger than ~50 nm behave as effective scattering centers, coupling light into waveguided modes and extending optical path length [1], [4], [7].

- **Near-Field Enhancement**

Nanoparticles that are less than 50 nm in size can focus electromagnetic fields, which makes it easier for them to absorb light within a few nanometers of their surface. This is very useful for ultrathin solar absorbers [6], [10], and [14].

- **Hot-Carrier Generation**

Non-radiative plasmon decay produces energetic electrons and holes that can be extracted across Schottky barriers [8], [11], thereby promoting the advancement of hot-carrier photovoltaics.

- **Hybrid Photonic–Plasmonic Modes**

When plasmonics are combined with photonic crystals or metasurfaces, they create hybrid resonances that make the system more efficient by lowering ohmic losses [19], [20], [21].

III. MATERIALS FOR PLASMONIC NANOPARTICLES

Material Type	Examples	Advantages / Special Features	Limitations	Refs.
Noble Metals	Silver (Ag)	• Strong LSPR in visible range • High scattering efficiency	Prone to oxidation and degradation	[1], [3], [7]
	Gold (Au)	• Chemically stable • Broadband plasmonic	Higher intrinsic optical losses	[6]

		response • Easy surface functionalization		
Aluminum (Al)	–	• Supports UV–visible plasmon resonances • Abundant and low-cost • CMOS-compatible for large-scale fabrication	Susceptible to surface oxide formation	[5]
Alternative Low-Loss Materials	Titanium Nitride (TiN)	• High thermal stability • Metallic behavior in visible/NIR • Lower cost than noble metals	Higher losses than Ag in the visible range	[22]
	Graphene	• Supports tunable plasmonic modes • Extremely thin and flexible • Electrically tunable carrier concentration	Requires complex fabrication; plasmonic activity is weaker in the visible range.	[23]
	Transparent Conductive Oxides (TCOs)	• Low optical damping • Compatible with silicon processing • Suitable for large-area integration	Limited plasmonic performance in the visible spectrum	[14]

IV. NANOPARTICLE GEOMETRIES AND DESIGN

- **Spherical Nanoparticles**

The most common type of nanoparticles used in plasmonic structures are spherical ones. This is because Mie theory [3], [10] can easily model how they act because they have a simple, symmetrical shape. The size of the particles, the type of metal (Au or Ag), and the refractive index of the medium around them all affect how they scatter, absorb, and enhance near fields. Small spheres (<50 nm) have absorption-dominated LSPR, while larger spheres (>80 nm) can provide strong scattering, hence their effectiveness in light trapping for thin-film and silicon solar cells. Thus, this predictable and tunable response makes it a fundamental choice for plasmon-enhanced photovoltaics.

- **ii. Nanorods, Nanodisks, Nanostars**

Anisotropic geometries of NPs, such as nanorods, nanodisks, and nanostars, offer new possibilities for tuning the plasmonic resonances. These shapes support several LSPR modes, improved polarisation sensitivity and broad or narrowband spectral tuning depending on the aspect ratio or structural features [13], [19].

1. Nanorods support transverse and longitudinal modes. Resonances can be tuned from the visible to the NIR regions.
2. Nanodisks provide large scattering cross-sections and narrow linewidths suitable for wavelength-selective enhancement.
3. Nanostars with sharp protruding tips provide intense "hot spots" that greatly enhance near-field enhancement and the generation of hot carriers.

These types of anisotropic designs are commonly used to improve light absorption in perovskite and thin-film photovoltaic devices.

- **Core–Shell Architectures**

Core-shell nanoparticles in principle comprise a metallic or dielectric core enveloped in a shell, typically SiO2, TiO2, or Al2 O3. All these designs have successfully shown reducing ohmic losses and improving the overall plasmonic performance. The dielectric shells weaken the non-radiative damping, enhance the efficiency of the scattering, stabilize metals like Ag against oxidation, and make precise tuning of the resonance wavelength possible. Semiconductor shells can further serve as electron-transport layers, allowing for more efficient extraction of hot carriers. Core-shell designs therefore offer improved optical control, stability, and compatibility with the absorber layers of solar cells.

- **Metasurfaces and Periodic Arrays**

Ordered 2D nanoparticle arrangements on metasurfaces and periodic plasmonic arrays support collective plasmonic resonances, including surface lattice resonances and Fano-type interference effects. These collective modes yield sharper, stronger, and more directionally controlled optical responses as compared to isolated nanoparticles. Engineering of array spacing, symmetry, and geometry allows for efficient diffraction of light by metasurfaces into the guided modes of the absorber layer, hence significantly enhancing broadband light trapping. Phase and polarization control can also be achieved in the designs of metasurfaces, making them attractive for integration into next-generation ultrathin and tandem photovoltaic architectures.

V. DEVICE INTEGRATION APPROACHES

- **Front-Side Plasmonic Nanoparticles**

Incident light is scattered into the absorber by NPs. This enhances the short-circuit current, especially in thin-film silicon devices [3], [4], [16].

- **Back Reflector Integration**

Metal nanoparticles positioned near the back surface enhance long-wavelength absorption by scattering and coupling to guided modes [4], [14].

- Embedded Nanoparticles in the Active Layer

This can enhance the local absorption and possible hot-carrier collection but may increase the recombination if not optimized [7], [8], [11].

- **Plasmonics in Perovskite and Organic Solar Cells**

Plasmonic NPs enhance the crystallinity, reduce trap states, and improve optical absorption of perovskites [12], [17].

Consequently, organic cells realize two benefits: increased absorption and exciton dissociation enhancement.

VI. MODELLING AND SIMULATION TECHNIQUES

- **COMSOL Multiphysics (FEM)**

Widely used for plasmonic field mapping, heat distribution, and coupled optical-electrical simulations.

- **FDTD Solvers (Lumerical)**

Offer accurate modelling of scattering, near-fields, and spectrum-dependent performance [5], [13].

- **Analytical Mie Theory**

Useful for spherical nanoparticle scattering and absorption calculations [10].

- **Machine Learning Optimization**

AI-driven optimization accelerates nanoparticle geometry, spacing, and spectral tuning.

VII. CHALLENGES AND LIMITATIONS

The main issues that make it hard to use these materials on a large scale are:

- Metal oxidation and perovskite instability [12], [14],
- Heat generation from plasmonic absorption [8]
- Ohmic losses and recombination near metal interfaces [7], [16]
- Difficulty in uniform deposition of nanoparticles [3], and
- Lack of reproducibility on an industrial scale [14], [15]

VIII. FUTURE RESEARCH DIRECTIONS

Promising future directions include:

- Low-loss plasmonic materials such as TiN and doped oxides [22],
- Hybrid metasurface–plasmonic systems [19], [21],
- Hot-carrier extraction schemes [8], [11],
- Self-assembled monolayer nanoparticle arrays [17],
- AI-driven nanophotonic design frameworks [24],
- These technologies are being integrated into tandem perovskite–silicon devices [12], [14].

IX. CONCLUSION

Plasmonic nanostructures have huge potential to enhance next-generation solar cell technologies due to the various mechanisms at play, such as LSPR, scattering, near-field enhancement, and hot-carrier generation. Plasmonics, therefore, accommodates a rich platform for optical management and efficiency improvement. Advances in materials engineering, theoretical modeling, and device integration are foreseen to accelerate practical implementation. These may enable future scalable, high-efficiency plasmonic photovoltaics with hybrid plasmonic-photonic metasurfaces, AI-based optimization, and robust materials

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