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Review of Progress on Plasmonic Enhanced Solar Cells

Cynthia Mwansa, Reccab Ochieng Manyala, Geoffrey Chanda

Abstract: ***Developments in plasmonic photovoltaics have yielded new mechanisms of trapping light. In this review, we provide an overview of the light-trapping mechanisms to improve the efficiency of solar cells. Specifically, this work presents a concise review and addresses factors such as light absorption, light scattering, near-field enhancement, and localised surface plasmons. Light absorption and charge recombination are the major limiting factors affecting the efficiency of photovoltaic solar cells. The review also examines emerging theories and their relationship to technologies involving plasmonic materials. The use of metallic nanoparticles in solar cells enables the occurrence of surface plasmon resonance (SPR). Surface plasmon resonance occurs when light excites the electrons at the metal surface, causing electrons in the metal to become excited and move parallel to the surface. The surface plasmon resonance induces a resonance effect that occurs when the conduction electrons of metal nanoparticles interact with incident photons. This resonance effect generates an oscillating electric field that drives the conduction electrons to oscillate coherently, inducing a localised surface plasmon (LSP). These localised surface plasmon results in absorption and scattering of light. Light is deflected or re-radiated by the metallic nanoparticles due to the excitation of localised surface plasmons. Hence, plasmonic metallic nanoparticles improve the efficiency of solar cells by concentrating or trapping light at the absorber layer. The dimensions, such as size and shape of the nanoparticles, directly influence both light scattering and near-field enhancement. The elongated nanoparticles interact more effectively with light than spherical nanoparticles, resulting in improved light absorption and enhanced solar cell efficiency.***

Keywords: ***Plasmonics, Light-Rapping, Nanoparticles, Plasmonic Resonance***

Abbreviations:
Al: Aluminum
ETL: Electron Transporting Layer
HTL: Hole Transporting Layer
ITO: Indium Tin Oxide
LSPs: Localised Surface Plasmons
NPs: Nanoparticles
OSC: Organic Solar Cell
PSC: Polymer Solar Cell
SPP: Surface Plasmon Polaritons
SPR: Surface Plasmon Resonance

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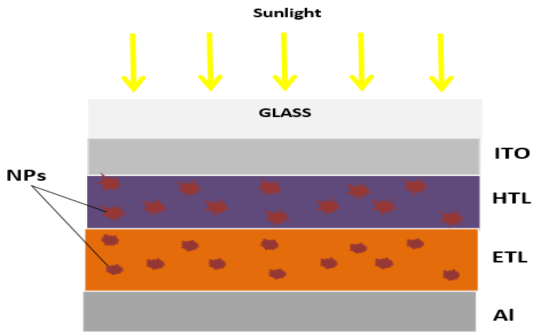
I. INTRODUCTION

The world's most significant challenge currently is the generation of clean and renewable energy [1]. Despite the Sun's energy being inexhaustible, efficient use of it has been a challenge [2]. Enhancement in light conversion efficiency is one of the leading research targets that will help in fulfilling the global demand for energy [3]. There are four problems associated with efficient light harvesting in solar cells. These problems include: light absorption, charge separation, charge migration, and charge recombination [4]. To boost light absorption, nanophotonic light-trapping mechanisms are being explored in Plasmonic Solar Cells (PSCs). Plasmonic solar cells are solar cells that convert light energy to electrical energy with the aid of plasmons. The interface between the metal and the dielectric semiconductor facilitates the support of surface plasmons. Plasmonic elements enhance solar cell efficiency by concentrating or trapping light within the absorber layer [5]. Plasmonic elements also serve as a back contact or as an anti-reflective electrode [6]. The incident light of the resonance frequency of the plasmon causes electron oscillations at the nanoparticle surface, which are captured by the conductive layer and produce an electrical current [7]. Plasmonic solar cells were developed as a solution for overcoming the restricted light absorption in thin film photovoltaic devices, and consequently, different plasmonic solar cell types have been developed [8]. Techniques for light trapping and localising have become more feasible in plasmonics [9] Plasmonic light trapping by metallic elements is of specific interest for the enhancement of thin film solar cell efficiency. Plasmonic effects are beneficial platforms for strong light scattering and are effectively and physically relevant for high-efficiency light harvesting in organic solar cells. Figure 1 depicts one of the architectures of PSCs.



[Fig.1: Device Architecture of PSCs with Embedded NPs in the HTL and ETL] [9]

The metallic nanoparticles placed on top of a solar cell, scatter the incident sunlight, coupling and trapping freely propagating plane waves into

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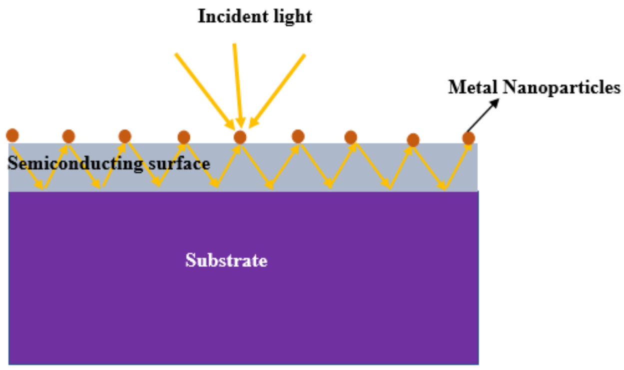
the active absorbing thin film [10]. When metallic nanoparticles are embedded within the active layer, they function as sub-wavelength antennas, where the plasmonic near-field is coupled to the absorbing layer, thereby increasing the effective absorption cross-section. Light scatters more into a dielectric with a larger permittivity. This is because the dielectric polarizesmore in response to the electric field. A material with a higher permittivity stores more energy and is more resistant to external electric fields. Permittivity is a measure of a material's electric polarizability. It measures how easily light polarizes in response to an electric field. Hence, light scattering is caused by fluctuations in the dielectric constant. It is the fluctuations in the dielectric constant that bring about light scattering [11]. If a nanoparticle is placed close to the interface of the two dielectrics, the optical length is increased by the angular spread of the light into the dielectric [12]. The metal contact reflects the light towards the surface, where metallic nanoparticles are present, causing the light to scatter again and resulting in multiple passes of light through the solar cell [13]. The metallic nanoparticles are primarily composed of silver, gold, or copper due to their strong interaction with light [14]. The surface nanoparticle material, size, shape, refractive index of the medium, and distance from the active layer are key factors in determining the scattering and coupling effects. The choice of nanoparticle size, concentration, and location in the device results in an enhanced power conversion efficiency compared to standard organic solar cells (OSCs) [15].

II. WORKING PRINCIPLE OF PLASMONICS

Plasmonic solar cells utilise metallic nanoparticles to enhance light absorption in thin-film solar cells. The use of plasmonic elements improves the efficiency of thin-film photovoltaics by focusing or trapping light within the absorber layer [8]. The working principle of plasmonics operates based on:(i) Light scattering, (ii) Near-field concentration of light, (iii) Surface plasmon resonance, and (iv) electron oscillations [16].

A. Light Scattering

Light scattering is how light behaves when it interacts with a medium containing a particle. When light encounters particles smaller than its wavelength, it is scattered in various directions. The scattering is dependent on the size of the particle and the wavelength of light, as shown in Figure 2. The interface between a metal and a semiconductor helps support surface plasmons. In plasmonics, light is deflected or re-radiated by the metallic nanoparticles as a result of the excitation of localised surface plasmons (LSPs) [17]. LSPs refer to a collective oscillation of electrons on the nanoparticle's surface, which leads to enhanced scattering compared to particles of similar size without plasmonic properties.In essence, these nanoparticles scatter light significantly at specific wavelengths matching their plasmon resonance frequency [18].



[Fig.2: Plasmonic Light-Trapping by Metal Nanoparticles]

Plasmonic metallic elements have been used to improve the efficiency of the solar cells by concentrating or trapping light at the absorber layer. These plasmonic elements serve as a back contact or as an anti-reflective electrode [19]. The incident light at the resonance frequency of the plasmon induces the electron oscillations at the interface of the electrode, thereby leading to the generation of surface plasmon polaritons, which are a collective oscillation of the free electrons [20]. The interaction of light with these oscillations enhances the electromagnetic field at the nanoparticle surface, thus producing the electrical current [21].

B. Near-Field Concentration of Light

Near-field light is the light that exists near the surface of an object. Plasmon near-field arises due to localised surface plasmons and boosts the light scattering, which increases the light absorption [19]. The interaction of the light with the small NPs increases the localised plasmonic resonance due to near-field enhancement, which in turn causes an increase in absorption. The plasmonic near-field, when coupled with the active layer, increases the absorption of light in the presence of nanoparticles [22]. In these materials, near-field light is utilised to enhance the electromagnetic field near the material's surface, thereby creating hot spots where light is significantly amplified.

C. Surface Plasmon Resonance

Surface plasmon resonance (SPR) occurs when light strikes the metal surface at a specific angle, causing electrons in the metal to become excited and travel parallel to the surface [23]. SPR is the significance of a resonance effect that occurs when the conduction electrons of metal nanoparticles interact with incident photons [24]. When small spherical metallic nanoparticles interact with light, the oscillating electric field drives the conduction electrons to oscillate coherently [25]. The oscillation of the electron cloud is a direct result of the restoring force that arises from Coulombic attraction between electrons and nuclei. This process results in a localised surface plasmon, as depicted in Figure 3.

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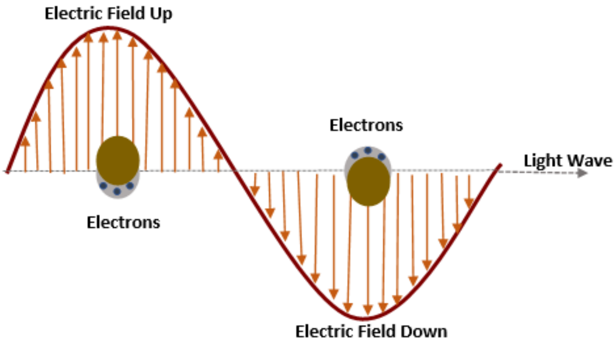

[Fig.3: Localised Surface Plasmon: Incident Light on Metal Nanoparticles Causes the Conduction Band Electrons to Oscillate]

The interaction of light and nanoparticles relies on the dimensions and shape of the metallic nanoparticles. The surface plasmon resonances manipulate light beyond the diffraction limit of light and create a localised electromagnetic field at the metallic surface.

D. Electron Oscillations

Plasmonics are free electron oscillations in a conducting material that manipulate light at the nanoscale level. Plasmons guide and confine light on the subwavelength scale. Electron oscillation is the periodic movement of an atomic electron in response to an imposed electromagnetic field, characterised by displacement, velocity, and acceleration synchronised with the frequency of the field. Electrons moving back and forth generate electromagnetic waves that spread outwards, thereby creating a ripple effect. In plasmonic materials, these electron oscillations give rise to surface plasmon resonance, which enhances the interaction of light with the material.

When light strikes metal nanoparticles, surface plasmons are activated, resulting in both scattering and absorption. The scattered light moves along the solar cell back and forth between the substrate and the nanoparticles, thereby enabling the solar cell to trap light further [9]. Light at the plasmonic resonance frequency triggers electron oscillations on the nanoparticle surface [26]. These electron oscillations are then captured by the conductive layer, generating an electrical current. The electrolyte potential in contact with the nanoparticles and the band gap of the conductive layer determine the resulting voltage. The dimensions and form of the nanoparticles, along with their placement within the cell, influence the overall solar cell efficiency [5]. Nanoparticle size is a recognized factor in determining both the local electric field and optical extinction. For instance, the use of two different-sized NPs can lead to synergy in the absorption of light at both short- and long-term wavelengths [27], thereby decreasing the loss of light within the cell. Increasing the size of the particle causes a red shift in the localised surface plasmon resonance wavelength [28]. The shape affects the uptake of the nanoparticles by the solar cells. The elongated nanoparticles exhibit stronger surface plasma resonances compared to spherical nanoparticles, as observed in the case of gold nanorods versus spheres. This is because the elongated nanoparticles have a higher ability to interact with more light-absorbing sites within the solar cell, thereby leading to potentially improved light absorption and enhanced solar cell efficiency [29]. On the other hand, the location of these NPs in solar cells affects the absorption and performance enhancement mechanisms. For instance, NPs placed at the back of the solar cell's surface scatter light into the active layer, hence enhancing the probability of absorbing photons [30]. The mechanisms used in the plasmonic enhancement of Organic Solar Cells make use of the near-field enhancement and efficient far-field [31]. The near-field enhancement occurs when light interacts with metallic nanoparticles, hence causing localised oscillations of electrons on the surface, thereby creating a strong electric field concentrated near the particle [32]. This strong field raises the likelihood of exciton creation in the surrounding organic material [33]. The intensity of the near-field effect is strongly tied to the nanoparticles' dimensions and the arrangement in terms of spacing between the nanoparticles [34]. Conversely, the far-field enhancement uses the scattering of light by plasmonic nanoparticles, hence redirecting light back into the active layer of the OSC [35]. This action effectively increases the optical path length, thereby allowing more light to be back-reflected into the active layer of the OSC. The near-field enhancement is optimised by controlling the size and shape of the nanoparticles and their arrangement [36]. Surface plasmon resonance (SPR) provides an alternative approach to enhancing the functionality of solar cells.SPR arises when light energises the electrons at the metal surface [37]. This excitation leads to coherent electron charge oscillations within metallic nanoparticles, which are stimulated by light [38]. These oscillations, in turn, generate a localised electric field near the surface of the nanoparticle, thereby strengthening the local electric field near the nanoparticle surface.

III. LIGHT TRAPPING MECHANISMS

Plasmonic nanoparticles (NPs) can improve the light trapping mechanisms by utilising spectral modification techniques to move unabsorbed frequencies of the light spectrum into the area of maximum cell absorption through light scattering and focusing the electromagnetic field into the active region of the device [39]. Surface plasmons support the light trapping. The surface plasmons are a collective oscillation of the conduction electrons in metals linked to the light oscillations in metals [40]. The interaction of light with metallic nanoparticles induces oscillations of the free electrons on the metal's surface, known as surface plasmons. If the nanoparticles are small and isolated, these plasmons are localised. However, at the metal-dielectric interface, these oscillations can propagate along the surface, forming surface plasmon polaritons (SPP). These SPPs effectively guide and concentrate light at the interface [41].

A. Surface Plasmonic Effect of Metallic Nanoparticles

The excited localised surface plasmon resonance of the metal nanoparticles under light illumination can be incorporated to improve light harvesting in various devices effectively [17]. This unique property of these nanoparticles is effective for light absorption in devices such as solar cells. The plasmonic nanoparticles (NPs) exhibit excellent optical properties, such as localised surface plasmon resonance (LSPR). LSPR is an optical phenomenon that occurs when light interacts with conductive nanoparticles that are smaller than the wavelength of the light. The electromagnetic field of the light incident on the plasmonic NP stimulates the electrons in the particle, hence making them move simultaneously [42]. Localised surface plasmon resonance excitation of noble metal nanoparticles (NPs) under light illumination can be effectively incorporated to improve light harvesting in devices [43].

B. Plasmonic NPs in Hole Transporting Layer (HTL)

Plasmonic nanoparticles are incorporated into the HTL material to improve the performance of PSCs. The plasmonic NPs improve performance by enhancing the photoelectric performance through the extraction and transportation of charges [44]. The embedded nanoparticles increase the roughness and the surface area of the transport layers, and thus provide good adhesion with the active layer and consequently enhance the extraction of charge carriers [45]. The nanoparticles can improve the charge extraction and transportation by accelerating the charge carrier extraction [46]. The nanoparticles can also accelerate the extraction of charge carriers from one material to another [47]and increase charge carrier mobility. The NPs increase the mobility of charge carriers by introducing dopant states [48]. Dopants are new energy levels in the band gap of a semiconductor that are created by adding impurities or dopants to the semiconductor material. NPs can enhance light absorption in the HTL by improving light harvesting in the active layer through enhanced light scattering, the near-field effect, and plasmon-induced charge separation. NPs are used to mitigate charge carrier recombination when placed in the interfacial layers of the solar cells. This, in turn, improves the stability of PSCs [43].

C. Plasmonic NPs in the active layer

Plasmonic NPs embedded in the active layer of the solar cell can improve the cell's efficiency by enhancing light absorption and increasing the production of electron-hole pairs [49]. The interaction of light incident on the OSCs and plasmonic NPs helps to create an electric field [50]. The field tends to increase the amount of light being trapped and absorbed in the active layer. On the other hand, the plasmonic NPs scatter light into the active layer, increasing the optical path length of light, [51] and hence further improving the absorption of light in the active layer [52]. This produces plasmonic-electric effects, effectively reducing the distance low-mobility holes travel while increasing the distance high-mobility electrons travel [53]. This, in turn, facilitates better carrier collection. Additionally, plasmonic nanoparticles can promote exciton generation, leading to an increase in free charge carriers [54].

IV. CONCLUSION

This document summarises recent advances in enhancing plasmonic cell performance. Based on the discussions in this article, we can conclude that improving the absorption of light in the activated area plays a vital role in enhancing performance. The plasmonic mechanisms that enhance the performance output of solar cells include light scattering, near-field concentration of light, surface plasmon resonance, and electron oscillations. Light scattering is improved by carefully considering the size and shape of the NPs. The elongated nanoparticles interact more with light and are considered superior to spherical nanoparticles. Near-field enhancement is highly dependent on the shape, size, and spacing of the nanoparticles, and hence can be optimised by controlling the shape, size, and arrangement of these nanoparticles. Electron oscillations generate localised surface plasmons, which strengthen the local electric field and thus, intensify light concentration.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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- **Data Access Statement and Material Availability:** The data and materials supporting the findings of this article are publicly accessible.
- **Authors' Contributions :** Each author has individually contributed to the article. Cynthia Mwansa: Conceptualization, writing the original draft of the article, reviewing and editing, Reccab Ochieng Manyala: Supervision, reviewing and editing, Geoffrey Chanda: Reviewing

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