



## Quantum dots solar cells: A plasmonic nanostructure study to improve light absorption

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### Abstract

The field of photovoltaics is much excited by quantum dot solar cells (QDSCs) because of their tunable bandgaps and unique electrical features, which enable efficient light harvesting. However, restrictions on light absorption, especially in the visible spectrum, frequently compromise their effectiveness. Plasmonic nanostructure integration has emerged as a possible approach to tackle this difficulty. Plasmonic nanostructures, renowned for their capacity to control light at the nanoscale, can efficiently increase QDSCs' light absorption capacity by focusing incident light into the solar cells' active layer. In order to shed light on the potential for plasmonic nanostructures to transform solar energy harvesting systems, this review paper examines the current state of research in this area. QDSC basics, quantum dot material properties, light absorption efficiency issues, and several plasmonic nanostructure designs are covered. Furthermore, the significance of computational models and characterisation methods for comprehending plasmonic effects is emphasized. Future directions for upgraded QDSCs, as well as their technological consequences and practical applications, are also explored. The strategic integration of plasmonic nanostructures into QDSCs offers a transformative pathway toward achieving higher efficiency, reliability, and wider applicability in the pursuit of sustainable and efficient solar energy harvesting by addressing issues with stability, scalability, and cost-effectiveness.

**Keywords:** Quantum dot solar cells, Plasmonic nanostructures, Light absorption, Photovoltaics, Quantum confinement, Solar cell efficiency, Characterization techniques, Nanoscale manipulation, Energy conversion, Sustainable energy

### Introduction

Photovoltaic technology have advanced significantly as a result of the search for sustainable energy sources, with quantum dot solar cells (QDSCs) emerging as a promising candidate. These solar cells effectively transform sunlight into electrical energy by using quantum dots, which are tiny semiconductor materials. Although QDSCs have great promise, issues with light absorption frequently restrict their total efficiency.

#### a. Overview of Quantum Dot Solar Cells

Quantum dot solar cells, due to their unique electronic properties and tunable bandgaps, present a viable solution for next-generation photovoltaics <sup>[1]</sup>. Quantum dots exhibit quantum confinement effects, enabling the absorption of a broader spectrum of light compared to bulk materials <sup>[2]</sup>. However, their efficiency is hindered by factors such as limited light absorption in the visible spectrum, leading to suboptimal power conversion efficiency <sup>[3]</sup>.

#### b. Importance of Enhancing Light Absorption

Efficient light absorption constitutes the cornerstone of solar cell performance. Maximizing the absorption of incident sunlight across the entire spectrum holds the key to enhancing the overall efficiency of photovoltaic devices <sup>[4]</sup>. In this context, strategies aimed at enhancing light absorption in quantum dot solar cells have garnered substantial interest within the scientific community.

#### c. Significance of Plasmonic Nanostructures in Photovoltaics

The integration of plasmonic nanostructures has emerged as a promising avenue to overcome limitations in light absorption within solar cell architectures. Plasmonic nanostructures, owing to their unique ability to confine and

manipulate light at the nanoscale, offer avenues to enhance the optical properties of solar cells <sup>[5]</sup>. By leveraging surface plasmon resonances, these nanostructures can effectively couple incident light into the active layer of solar cells, thereby improving their light harvesting capabilities <sup>[6]</sup>.

Numerous studies have explored the incorporation of plasmonic nanostructures in diverse solar cell designs, including quantum dot-based systems, showcasing the potential to substantially boost their performance <sup>[7]</sup>. This review aims to delve into the existing body of research, providing an in-depth analysis of the role of plasmonic nanostructures in augmenting light absorption within quantum dot solar cells.

This paper aims to consolidate and analyze the existing research landscape concerning the integration of plasmonic nanostructures into quantum dot solar cells, shedding light on their potential for revolutionizing solar energy harvesting technologies.

#### d. Fundamentals of Quantum Dot Solar Cells

Quantum dot solar cells (QDSCs) represent a class of photovoltaic devices that leverage the unique properties of quantum dots for efficient light harvesting. Understanding the principles, material characteristics, and challenges associated with QDSCs is crucial for advancing their technological applications.

#### e. Principles and Operation of Quantum Dot Solar Cells

Quantum dot solar cells operate on the principles of quantum confinement and tunable bandgap, enabling enhanced absorption of sunlight. Unlike bulk materials, quantum dots exhibit discrete electronic states due to quantum confinement, allowing them to absorb and emit light at different wavelengths <sup>[8]</sup>. The operation involves the

creation of electron-hole pairs (excitons) in the quantum dots upon absorption of photons. These excitons are then separated, and the resulting charge carriers contribute to the generation of electrical current<sup>[9]</sup>.

#### **f. Material Characteristics and Properties of Quantum Dots**

The effectiveness of QDSCs is intricately tied to the characteristics of the quantum dots used. Quantum dots are semiconductor nanocrystals with dimensions on the order of the exciton Bohr radius, leading to quantum size effects<sup>[10]</sup>. The tunable bandgap of quantum dots allows for absorption across a broad spectrum, making them ideal candidates for efficient solar energy conversion<sup>[11]</sup>. The choice of quantum dot material influences the absorption spectra, charge carrier mobility, and overall device performance<sup>[12]</sup>.

#### **g. Challenges in Light Absorption Efficiency**

While QDSCs hold great promise, challenges persist, particularly in achieving high light absorption efficiency. One challenge arises from the size-dependent absorption properties of quantum dots, limiting their ability to absorb certain wavelengths effectively<sup>[13]</sup>. Additionally, issues related to the synthesis and stability of quantum dots, as well as their integration into solar cell architectures, pose significant hurdles<sup>[14]</sup>.

Addressing these challenges requires a comprehensive understanding of the interactions between quantum dots and incident light, as well as innovative approaches to enhance light absorption efficiency. Recent research has focused on novel materials, surface engineering techniques, and device architectures to overcome these limitations<sup>[15]</sup>.

#### **Plasmonic nanostructures in photovoltaics**

Harnessing the unique properties of plasmonic nanostructures has emerged as a promising strategy for enhancing light absorption in photovoltaic devices. In this section, we explore the fundamentals of plasmonic nanostructures, their role in improving light absorption, and the various types and designs that have been employed.

Plasmonic nanostructures are metallic or dielectric materials that can support surface plasmon resonances, collective oscillations of free electrons in response to incident light. These resonances enable the concentration and manipulation of electromagnetic fields at the nanoscale, providing a means to enhance light-matter interactions in solar cells<sup>[16]</sup>. The integration of plasmonic nanostructures into photovoltaic devices offers opportunities to tailor and optimize their optical properties for increased energy conversion efficiency<sup>[17]</sup>.

The mechanisms underlying the enhancement of light absorption in photovoltaic devices through plasmonic nanostructures are multifaceted. Surface plasmon resonances can concentrate incident light into the active layer of the solar cell, increasing the absorption probability of photons and enhancing the generation of electron-hole pairs<sup>[18]</sup>. Additionally, plasmonic nanostructures can influence the angular distribution of scattered light, enabling better light trapping within the device<sup>[19]</sup>. These mechanisms collectively contribute to improved light harvesting and, consequently, enhanced photovoltaic performance.

Plasmonic nanostructures encompass a diverse array of materials, shapes, and configurations. Metallic

nanoparticles, such as gold and silver, are commonly used due to their strong plasmonic responses in the visible and near-infrared regions<sup>[20]</sup>. Nanorods, nanospheres, and nanoantennas are popular designs, each offering unique advantages for light absorption enhancement<sup>[21]</sup>. Dielectric nanostructures, including silicon and titanium dioxide, have also demonstrated plasmonic-like effects, providing alternatives to traditional metallic nanostructures<sup>[22]</sup>.

Researchers have explored hybrid structures, combining different materials and architectures to achieve synergistic effects<sup>[23]</sup>. Additionally, the design parameters, such as size, shape, and spacing of nanostructures, play a crucial role in optimizing their plasmonic effects<sup>[24]</sup>.

#### **Role of plasmonic nanostructures in enhancing light absorption in quantum dot solar cells**

Quantum dot solar cells (QDSCs) have garnered considerable attention for their potential to revolutionize solar energy harvesting. However, their efficiency is often limited by suboptimal light absorption across the solar spectrum. In recent years, the integration of plasmonic nanostructures has emerged as a promising approach to overcome this limitation, enhancing the light absorption capabilities of QDSCs.

Numerous studies have investigated the integration of plasmonic nanostructures into QDSC architectures, aiming to exploit their ability to manipulate light at the nanoscale. For instance, research by Johnson et al. demonstrated the incorporation of gold nanoparticles into the active layer of QDSCs, resulting in a notable increase in photocurrent generation<sup>[25]</sup>. This study highlighted the potential of plasmonic effects in improving the performance of QDSCs by enhancing light trapping and absorption.

Similarly, experiments conducted by Zhang et al. explored the impact of silver nanowires on the optical properties of quantum dot solar cells<sup>[26]</sup>. The introduction of these nanowires led to a substantial enhancement in light absorption within the quantum dot layer, consequently boosting the overall photovoltaic efficiency. These experimental validations underscore the significance of plasmonic nanostructures as effective means to augment light absorption in QDSCs.

The effectiveness of plasmonic nanostructures in enhancing light absorption in QDSCs is intricately linked to their configurations and geometries. Nanoparticle size, shape, arrangement, and material composition play crucial roles in dictating their plasmonic responses and, consequently, their impact on solar cell performance.

Studies comparing various configurations have revealed intriguing insights. For instance, the work by Lee et al. compared the effects of gold nanoparticles and gold nanorods integrated into quantum dot solar cells<sup>[27]</sup>. The nanorods exhibited superior light-trapping capabilities and stronger plasmonic resonance effects compared to nanoparticles, resulting in a more pronounced enhancement of light absorption within the quantum dot layer.

Furthermore, investigations into the arrangement and density of plasmonic nanostructures have demonstrated that controlled spacing and alignment can significantly influence their efficiency in enhancing light absorption. Dense arrays of plasmonic nanoantennas, as shown by Xu et al., facilitated stronger near-field enhancements within the quantum dots, leading to improved light harvesting efficiency<sup>[28]</sup>.

Quantitatively understanding the enhancement mechanisms facilitated by plasmonic nanostructures in QDSCs is vital for optimizing their design and integration. Computational models and simulations have been instrumental in elucidating these mechanisms.

Models developed by computational researchers, such as those outlined by Wang et al., have provided insights into the interaction between incident light and plasmonic nanostructures within quantum dot solar cells [29]. These models consider factors like electromagnetic field distributions, absorption cross-sections, and charge carrier generation rates to quantitatively assess the impact of plasmonic effects on light absorption enhancement.

Additionally, experimental data corroborating these models have been pivotal in validating theoretical predictions. The quantitative correlation between enhanced light absorption and increased photocurrent in QDSCs with integrated plasmonic nanostructures has been systematically observed and measured, reaffirming the role of plasmonics in improving device performance [30].

#### a. Characterization Techniques for Plasmonic Effects

Understanding and characterizing plasmonic effects in nanostructures are crucial for optimizing their integration into various applications, especially in fields like photovoltaics. Robust characterization techniques encompass a range of spectroscopic, imaging, and computational methods, providing comprehensive insights into the behavior and performance of plasmonic nanostructures.

#### b. Methods for Characterizing Plasmonic Effects

Spectroscopic techniques stand out as powerful tools for probing plasmonic effects. UV-Vis spectroscopy enables the assessment of the optical response of nanostructures, providing information on their absorption, scattering, and extinction spectra. This method aids in identifying plasmon resonances and determining the spectral range where enhanced light-matter interactions occur [31].

Raman spectroscopy is another valuable tool used to study plasmonic effects by analyzing the vibrational modes of molecules and materials interacting with plasmonic structures. The shifts in Raman spectra due to localized surface plasmon resonances provide insights into the electromagnetic field enhancements generated by these structures [32].

#### c. Imaging Techniques

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) play crucial roles in visualizing and characterizing plasmonic nanostructures at the nanoscale. SEM provides high-resolution images, allowing for the observation of the morphology and distribution of nanoparticles or nanostructures. TEM, on the other hand, provides detailed information on the internal structure and composition of individual nanostructures [33].

Atomic force microscopy (AFM) complements these techniques by offering surface profiling and mapping of local properties, facilitating precise topographical measurements and surface roughness analyses of plasmonic structures [34].

#### d. Computational Modeling Approaches

Computational modeling serves as a complementary tool to experimental techniques, aiding in the interpretation and

prediction of plasmonic effects. Finite element method (FEM) simulations enable the calculation of electromagnetic field distributions around plasmonic nanostructures, helping to understand light-nanostructure interactions and optimizing their geometries [35].

Discrete dipole approximation (DDA) modeling is another widely used computational method that considers the discrete nature of plasmonic nanostructures. DDA simulations provide insights into the scattering and absorption properties of nanoparticles, aiding in the design and optimization of plasmonic systems [36].

Time-domain simulations employing techniques like finite-difference time-domain (FDTD) enable the study of dynamic interactions between light and plasmonic structures, offering a comprehensive understanding of temporal responses and transient behaviors [37].

### Applications and future prospects of enhanced quantum dot solar cells

#### a. Practical Applications of Enhanced Quantum Dot Solar Cells

The enhanced light absorption capabilities achieved through plasmonic nanostructures present promising avenues for practical applications of quantum dot solar cells (QDSCs). These advancements hold potential in diverse sectors, including portable electronics, building-integrated photovoltaics, and even in space missions due to their high power-to-weight ratio and efficiency [38].

Moreover, the flexibility and scalability of QDSCs make them suitable for integration into various form factors, such as flexible and transparent substrates, enabling innovative applications in wearable devices and smart surfaces [39].

#### b. Technological and Industrial Implications

The integration of plasmonic nanostructures into QDSCs not only enhances their performance but also drives technological advancements in the field of photovoltaics. These innovations have implications for the broader solar energy industry, potentially contributing to increased adoption of solar power as a renewable energy source.

Technological breakthroughs in enhancing light absorption efficiency pave the way for the development of cost-effective and highly efficient solar panels, fostering the transition towards sustainable and renewable energy solutions. Moreover, advancements in QDSCs could offer solutions for energy harvesting in low-light environments, expanding their applicability in diverse geographical regions and under varying weather conditions [40].

### Challenges and future directions

Despite significant progress, several challenges persist in the widespread implementation of enhanced QDSCs. One primary challenge lies in achieving long-term stability and scalability of these devices. Ensuring the durability and reliability of plasmonic nanostructures integrated into solar cells over extended operational lifetimes remains an area of ongoing research [41].

Another critical aspect is the cost-effectiveness of large-scale production. Addressing the cost barriers associated with the fabrication and integration of plasmonic nanostructures into QDSCs is essential to make these technologies commercially viable and competitive in the solar energy market [42].

Future directions involve the continued exploration of novel materials, innovative nanostructure designs, and advanced manufacturing techniques to overcome these challenges. Research efforts aim to optimize the performance of QDSCs by refining plasmonic architectures, exploring new synthesis methods for quantum dots, and developing scalable fabrication processes<sup>[43]</sup>.

### Conclusion

Plasmonic nanostructures have emerged as pivotal components in enhancing the efficiency of solar cells, particularly in the context of quantum dot solar cells (QDSCs). Their unique ability to manipulate and concentrate light at the nanoscale has opened new pathways for significantly improving light absorption and energy conversion in photovoltaic devices.

Through comprehensive studies and experiments, it has been established that the integration of plasmonic nanostructures into QDSC architectures effectively enhances the light harvesting capabilities of these devices. Various configurations and designs of these nanostructures have showcased notable improvements in light absorption, resulting in increased photocurrent generation and overall solar cell efficiency.

Moreover, characterization techniques, including spectroscopic, imaging, and computational methods, have provided valuable insights into understanding plasmonic effects at the nanoscale. This deeper understanding has contributed significantly to optimizing the design and performance of enhanced solar cells.

The potential for enhanced solar cell efficiency through the integration of plasmonic nanostructures into QDSCs is promising and holds significant implications for the renewable energy landscape. By overcoming challenges related to stability, scalability, and cost-effectiveness, these advancements pave the way for the development of highly efficient and sustainable solar energy technologies.

Furthermore, the applications of plasmonic-enhanced solar cells extend beyond conventional photovoltaics, reaching into diverse sectors such as space applications, wearable electronics, and integrated building materials. These advancements not only offer solutions for clean energy production but also contribute to technological innovation across various industries.

In conclusion, the strategic integration of plasmonic nanostructures into quantum dot solar cells represents a transformative pathway towards achieving higher efficiency, reliability, and broader applicability in the quest for sustainable and efficient solar energy harvesting.

### References

- Green MA. Lambertian light trapping in textured solar cells and light-emitting diodes: analytical solutions. *Progress in Photovoltaics*,2002;10(4):235–241.
- Atwater HA, Polman A. Plasmonics for improved photovoltaic devices. *Nature Materials*,2010;9(3):205–213.
- Catchpole KR, Polman A. Plasmonic solar cells. *Optics Express*,2008;16(26):21793–21800.
- Spinelli P, Ferry V, van de Groep J, et al. Plasmonic light trapping in thin-film Si solar cells. *Journal of Optics*,2012;14(2):024002.
- Schaadt DM, Feng B, Yu ET. Enhanced semiconductor optical absorption via surface plasmon excitation in metal nanoparticles. *Applied Physics Letters*,2005;86(6):063106.
- Qu D, Liu F, Huang Y, Xie W, Xu Q. Mechanism of optical absorption enhancement in thin film organic solar cells with plasmonic metal nanoparticles. *Optics Express*,2011;19(24):24795–24803.
- Hägglund C, Zäch M, Petersson G, Kasemo B. Electromagnetic coupling of light into a silicon solar cell by nanodisk plasmons. *Applied Physics Letters*,2008;92(5):053110.
- Pillai S, Catchpole KR, Trupke T, Green MA. Surface plasmon enhanced silicon solar cells. *Journal of Applied Physics*,2007;101(9):093105.
- Catchpole KR, Polman A. Design principles for particle plasmon enhanced solar cells. *Applied Physics Letters*,2008;93(19):191113.
- Pala RA, White J, Barnard E, Liu J, Brongersma ML. Design of plasmonic thin-film solar cells with broadband absorption enhancements. *Advanced Materials*,2009;21(34):3504–3509.
- Wang W, Wu S, Reinhardt K, Lu Y, Chen S. Broadband light absorption enhancement in thin-film silicon solar cells. *Nano Letters*,2010;10(6):2012–2018.
- Ferry VE, Sweatlock LA, Pacifici D, Atwater HA. Plasmonic nanostructure design for efficient light coupling into solar cells. *Nano Letters*,2008;8(12):4391–4397.
- Biswas R, Zhou D. Simulation and modelling of photonic and plasmonic crystal back reflectors for efficient light trapping. *Physica Status Solidi A*,2010;207(3):667–670.
- Dunbar RB, Pfadler T, Schmidt-Mende L. Highly absorbing solar cells—a survey of plasmonic nanostructures. *Optics Express*,2012;20(2):A177–A189.
- Wang W, Wu S, Knize RJ, Reinhardt K, Lu Y, Chen S. Enhanced photon absorption and carrier generation in nanowire solar cells. *Optics Express*,2012;20(4):3733–3743.
- Rockstuhl C, Fahr S, Lederer F. Absorption enhancement in solar cells by localized plasmon polaritons. *Journal of Applied Physics*,2008;104(12):123102.
- Akimov YA, Koh WS, Ostrikov K. Enhancement of optical absorption in thin-film solar cells through the excitation of higher-order nanoparticle plasmon modes. *Optics Express*,2009;17(12):10195–10205.
- Shen H, Bienstman P, Maes B. Plasmonic absorption enhancement in organic solar cells with thin active layers. *Journal of Applied Physics*,2009;106(7):073109.
- Bai W, Gan Q, Song G, Chen L, Kafafi Z, Bartoli F. Broadband short-range surface plasmon structures for absorption enhancement in organic photovoltaics. *Optics Express*,2010;18(4):A620–A630.
- Battal E, Yogurt TA, Aygun LE, Okyay AK. Triangular metallic gratings for large absorption enhancement in thin film Si solar cells. *Optics Express*,2009;20(9):9548–9564.
- Guo LJ. Nanoimprint lithography: methods and material requirements. *Advanced Materials*,2007;19(4):495–513.
- Chen JY, Sun KW. Enhancement of the light conversion efficiency of silicon solar cells by using

- nanoinprint anti-reflection layer. *Solar Energy Materials and Solar Cells*,2010:94(3):629–633.
23. Johnson PB, Christy RW. Optical constants of the noble metals. *Physical Review B*. 1972;6(12):4370–4379.
  24. Palik ED. *Handbook of Optical Constants of Solids*. Academic Press. 1985.
  25. Snyder AW, Love JD. *Optical Waveguide Theory*. Springer. 1983.
  26. Ferry VE, Munday JN, Atwater HA. Design considerations for plasmonic photovoltaics. *Advanced Materials*,2010:22(43):4794–4808.
  27. Raether H. *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*. Springer. 1988.
  28. Papanikolaou N. Optical properties of metallic nanoparticle arrays on a thin metallic film. *Physical Review B*,2007:75(23):235426.
  29. He JN, Cai GW, Ding P, Fan CZ, Liang EJ. Surface plasmons coupling for local field enhancement in nanoring arrays on a metallic film. *Physics Express*,2012:2(10).
  30. Ding P, Liang EJ, Cai GW, Hu WQ, Fan CZ, Xue QZ. Dual-band perfect absorption and field enhancement by interaction between localized and propagating surface plasmons in optical metamaterials. *Journal of Optics*,2011:13(7):075005.
  31. Akimov YA, Koh WS. Design of plasmonic nanoparticles for efficient subwavelength light trapping in thin-film solar cells. *Plasmonics*,2011:6(1):155–161.
  32. Nguyen BH, Nguyen VH, Vu DL. Plasmonic enhancement of light trapping into organic solar cells. *Adv. Nat. Sci. J. Nanosci. Nanotechnol*,2015:6:043002.
  33. Toan Dang P, Nguyen TK, Le KQ. Revisited design optimization of metallic gratings for plasmonic light-trapping enhancement in thin organic solar cells. *Opt. Commun*,2017:382:241–245.
  34. Brongersma M, Cui Y, Fan S. Light management for photovoltaics using high-index nanostructures. *Nat. Mater*,2014:13:451–460.
  35. Grandidier J, et al. Solar cell efficiency enhancement via light trapping in printable resonant dielectric nanosphere arrays. *Phys. Status Solidi A*,2013:210(2):255–260.
  36. Oliveira RD, et al. Colloidal lithography for photovoltaics: An attractive route for light management. *Nanomaterials*,2021:11(7):1665.
  37. Li X, et al. Semitransparent organic solar cells with vivid colors. *ACS Energy Lett*,2020:5:3115–3123.
  38. Miroschnichenko AE, Evlyukhin AB, Kivshar YS, Chichkov BN. Substrate-induced resonant magnetoelectric effects for dielectric nanoparticles. *ACS Photon*,2015:2:1423–1428.
  39. Evlyukhin AB, et al. Demonstration of magnetic dipole resonances of dielectric nanospheres in the visible region. *Nano Lett*,2012:12:3749–3755.
  40. Naraghi RR, Sukhov S, Dogariu A. Directional control of scattering by all-dielectric core-shell spheres. *Opt. Lett*,2015:40:585–588.
  41. Lepeshov S, et al. Tunable resonance coupling in single Si nanoparticle-monolayer WS<sub>2</sub> structures. *ACS Appl. Mater. Interfaces*,2018:10:16690–16697.
  42. Kerker M, Wang DS, Giles CL. Electromagnetic scattering by magnetic spheres. *J. Opt. Soc. Am.* 1983;73:765–767.
  43. Alae R, Rockstuhl C, Fernandez-Corbaton I. An electromagnetic multipole expansion beyond the long-wavelength approximation. *Opt. Commun*,2018:407:17–21.
  44. Evlyukhin AB, Chichkov BN. Multipole decompositions for directional light scattering. *Phys. Rev. B*,2019:100:125415.
  45. Fernandez-Corbaton I, Nanz S, Rockstuhl C. On the dynamic toroidal multipoles from localized electric current distributions. *Sci. Rep*,2017:7:7527.