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Review

Recent advances in increasing the efficiency of solar cells using gold nanostructures/quantum dots, a comprehensive review

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Abstract: Given the increasing demand for sustainable energy sources and the challenges associated with the limited efficiency of solar cells, this review focuses on the application of gold quantum dots (AuQDs) in enhancing solar cell performance. Gold quantum dots, with their unique properties such as the ability to absorb ultraviolet light and convert it into visible light expand the utilization of the solar spectrum in solar cells. Additionally, these quantum dots, through plasmonic effects and the enhancement of localized electric fields, improve light absorption, charge carrier generation (electrons and holes), and their transfer. This study investigates the integration of quantum dots with gold plasmonic nanoparticles into the structure of solar cells. Experimental results demonstrate that using green quantum dots and gold plasmonic nanoparticles as intermediate layers leads to an increase in power conversion efficiency. This improvement highlights the significant impact of this technology on solar cell performance. Furthermore, the reduction in charge transfer resistance and the increase in short-circuit current are additional advantages of utilizing this technology. The findings of this research emphasize the high potential of gold quantum dots in advancing next-generation solar cell technology.

Keywords: Au-Nano particles; Au-QDs; sustainable energy; solar energy; short circuit current

1. Introduction

In the last few decades, the rise in population and industrial advancement has placed greater demands on worldwide energy resources. Consequently, the necessity to discover sustainable and renewable energy supply solutions has arisen as one of the most pressing global issues. Among the various renewable energy sources, solar energy is notable as one of the top choices because of its extensive availability, sustainability, and low environmental impact. Nonetheless, numerous obstacles, such as the low efficiency of solar cells and their manufacturing expenses, persist in obstructing the complete achievement of this technology's capabilities. Recent studies have aimed at enhancing the efficiency and lowering the manufacturing expenses of solar cells. To enhance the effectiveness of solar cells, several solutions have been suggested, including the incorporation of different quantum dots. In their research, Ashkani and collaborators also noted the impact of Graphene on the efficiency of solar cells [1,2]. Additionally, a major advancement in this area is the use of gold quantum dots (AuQDs) technology. Gold quantum dots, because of their nanoscale dimensions and distinctive optical characteristics, are capable of absorbing ultraviolet light and transforming it into visible light. This ability enables more effective use of the solar spectrum and enhances energy conversion efficiency. Additionally, the plasmonic effects created by these quantum dots generate intense localized electric fields, which boost light absorption and electron transfer in solar cells. This article explores how gold quantum dots enhance solar cell efficiency and their potential to propel the future of solar technologies.

2. Solar energy and solar cells

2.1. Solar energy and its advantages over other energy sources

The increasing global energy demand is one of the most pressing challenges of the 21st century. Driven by population growth and industrial development, energy consumption continues to surge, underscoring the urgent need for sustainable and innovative energy solutions. Considering energy sources is therefore crucial, as they play a key role in satisfying the needs of the world's population. Accessible energy is insufficient for many people due to several factors, such as the developmental profile of a country, the economic status of its people, and the technological advancements within the country. The ecosystem is heavily polluted due to the emission of various gases generated from the burning of fossil fuels, which are readily available and commonly used to satisfy the world's energy demand [3]. It is therefore vital to shift toward eco-friendly energy sources for the betterment of the future world [4]. Renewable energy sources such as solar energy, wind energy, hydropower, and geothermal energy are critically important in this regard, as they are eco-friendly [5]. However, solar energy could be the best option for the future for several reasons. In general, sunlight as an energy source has many advantages. The sun is the largest natural energy source that is continuously available, and its energy is produced consistently. This energy is renewable, with the sun emitting it at a rate of 3.8×10^{23} kW, of which approximately 1.8×10^{14} kW is intercepted by the Earth [6]. Unlike fossil fuels, which have limited resources, the sun will continue to produce energy for billions of years. Moreover, the cost of installing solar systems has decreased due to their widespread adoption, making this technology more affordable every day. Additionally, solar energy production does not generate pollution and helps protect the environment. The use of solar energy can reduce dependence on foreign sources, which is especially important for countries that rely on importing fossil fuels. Today, with the help of storage systems, solar energy can also be utilized during non-daylight hours, such as at night or on cloudy days. Solar energy also has a significant impact on economic growth and job creation. **Table 1** also shows a summary of the increase in the volume of solar cell consumption in recent years, which requires further attention [7].

Table 1. Generating electrical energy with solar cells in recent years [7].

Year	Generating electrical energy (TWh per year)
2000	Less than 100
2004	Less than 100
2008	Less than 150
2012	150 up to 200
2016	400
2020	1000

2.2. Solar cells and their characteristics

Solar cells introduction

A solar cell (also known as a solar panel) is a device used to convert sunlight into electrical energy as can be seen in **Figure 1**. This process occurs through a phenomenon called the "photovoltaic effect". In this effect, when sunlight (which consists of photons) strikes the surface of a specific material, the photons can excite the electrons of that material, causing them to be released. These free electrons then move and create an electric current. To demonstrate the effectiveness of solar energy, the sunlight radiation on dark disks could provide energy for the entire world. If solar cells with a conversion efficiency of only 8% are installed in suitable positions all over the world, they could generate an average of 18 terawatts of electricity. This amount exceeds the total primary energy output currently obtained from all major energy sources, including coal, oil, gas, nuclear, and hydroelectric [8].

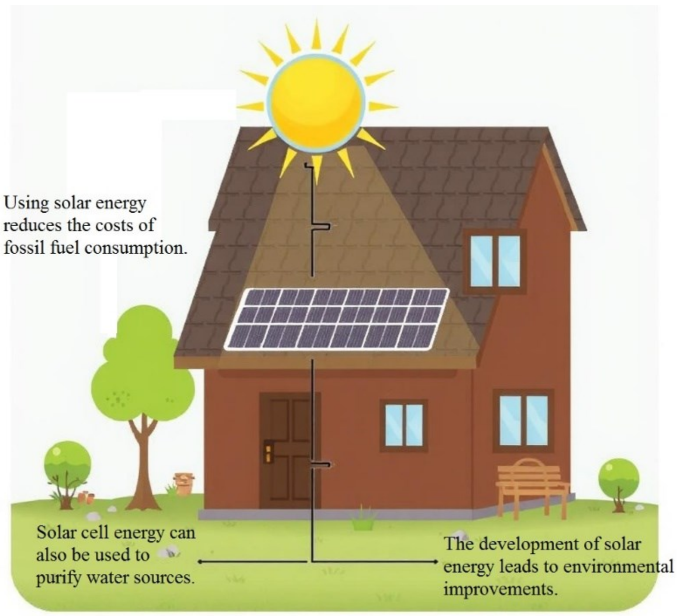

Figure 1. A schematic of the mechanism of utilizing solar energy for domestic use and its benefits.

3. Quantum dots and gold quantum dots

3.1. Introduction to quantum dots

Quantum dots (QDs) have been recognized as a significant advancement in nanotechnology, representing semiconductor inorganic crystals that contain varying numbers of electrons occupying well-defined, discrete quantum states. While QDs share a similar atomic arrangement with bulk materials, their three-dimensional truncation results in a higher proportion of surface atoms compared to bulk counterparts [9]. QDs are characterized by their small size, which allows for a wide range of element ratio variations, often leading to remarkable fluorescent properties [10]. These semiconductor nanoparticles exhibit unique features such as size-dependent emission wavelengths, a broad excitation spectrum, and the ability to emit glowing light when stimulated by UV light, resulting in fascinating optical phenomena [11,12]. Additionally, the structure of QDs can be precisely tailored, adhering to the principles of quantum confinement, which further enhances their versatility and potential for various applications [13]. The emission and absorption spectra corresponding to the energy band gap of quantum dots (QDs) [14] are governed by quantum confinement principles [15,16], which describe the energy required to excite electrons from the electronic band to higher energy levels. This excitation spontaneously creates an electron-hole pair, which can emit energy in the form of fluorescent photons [17]. QDs can also be viewed as artificial atoms that generate discrete energy levels, with their band gap being precisely modulated by varying their size [18]. The band gap is related to the Nano-crystallite size, as it depends on the number of atoms that make up the structure. As a result, QDs exhibit optical properties that depend on their size, with smaller nanocrystals having larger band gaps [19,20]. Specifically, the energy band gap increases as the quantum dot particle size decreases, leading to corresponding shifts in the wavelengths of emitted light [14].

3.2. Techniques for producing quantum dots

There are various widely known methods for producing quantum dots: Physical, chemical, and mechanical. There are also different definitions concerning the manufacturing and synthesis of quantum dots. Quantum dots’ fabrication involves processes generally divided into two main categories: Top-down and bottom-up methods. The choice of methods for fabricating Nano-materials depends on the type of material, the desired properties, and the final application. In general, bottom-up methods tend to offer greater precision and control, while top-down methods may be more suitable for larger scales and industrial applications [21].

3.2.1. Top-down methods

In top-down approaches, bulk materials are broken down into smaller parts to produce nanostructured materials. These methods include mechanical milling, laser ablation, etching, sputtering, and electro-explosion.

- Mechanical milling: In this method, materials are converted into smaller and nanometer-sized particles using high-speed mills or similar processes [22].
- Lithography: This method uses light or other beams to design precise patterns on the surface of materials, creating nanostructures [23].
- Laser ablation: In this process, a laser is used to vaporize and remove portions of the material, ultimately leading to the production of nanoparticles [24].

- Electro-spinning: Electro-spinning is a simple method to produce Nano-fibers, particularly from polymers, and coaxial electro-spinning enables large-scale production of core-shell and hollow Nano-fibers [25].
- Sputtering: Sputtering produces thin nanomaterial films by bombarding solid surfaces with high-energy particles, yielding high-purity materials with compositions similar to the target [26].
- Arc discharge method: This method generates carbon-based Nano-material (e.g., fullerenes, nanotubes, Graphene) using arc discharge between graphite rods in a helium atmosphere [27,28].

3.2.2. Bottom-up methods

Bottom-up methods in Nano-material involve assembling structures from atoms, molecules, or small precursors, enabling precise control over size, shape, and properties. Unlike top-down approaches that break down bulk materials, bottom-up techniques like self-assembly, sol-gel processes, and chemical vapor deposition utilize natural processes to create Nano-scale materials. These methods are widely used in electronics, energy storage, drug delivery, and catalysis, where Nano-scale precision enhances performance.

- Chemical vapor deposition (CVD): CVD produces high-quality Nano-material by depositing thin films through chemical reactions of vapor-phase precursors on heated substrates. It is widely used for carbon-based Nano-material like carbon nanotubes and Graphene, where catalysts determine the material's morphology [29].
- Hydrothermal and solvothermal methods: These methods synthesize nanostructures (e.g., nanowires, Nano-rods) through reactions in high-pressure, high-temperature environments. The hydrothermal process uses aqueous solutions, while Solvothermal employs non-aqueous media. Microwave assisted hydrothermal methods are gaining attention in nanomaterial engineering [30].
- Sol-gel method: The sol-gel method is a wet-chemical process for producing metal-oxide Nano-material. It involves precursor hydrolysis, condensation, aging, and calcination, leading to homogeneous, low temperature materials. This economical method supports complex nanostructures and composites [31].
- Soft and hard templating methods: Soft templating uses surfactants to form Nano-porous materials with tunable pore sizes, while hard templating involves filling solid templates with precursors to create mesoporous replicas. Both methods enable the production of diverse nanostructures like Nano-rods and mesoporous Graphene [32].
- Reverse micelle method: This method uses water-in-oil emulsions where reverse micelles act as Nano-reactors. By controlling the water-to-surfactant ratio, uniform nanoparticles with precise sizes are synthesized. It is a simple way to create fine, monodisperse Nano-reactors [33,34].

3.3. Gold quantum dots and their properties

Gold quantum dots (AuQDs) are nanoparticles that display unique electronic and optical properties due to quantum confinement effects. These characteristics make them highly valuable for a wide range of applications, particularly in optoelectronics and sensing. AuQDs possess discrete electronic states that lead to distinct optical behaviors, such as photoluminescence. The quantum confinement effect results in size-dependent optical absorption and emission spectra, allowing the optical properties of AuQDs to be tuned based on their size. This tunability is especially useful in applications like fluorescence resonance energy transfer (FRET) systems, where specific wavelength emissions are necessary for efficient energy transfer between molecules. **Figure 2** schematically shows some of the applications of gold quantum dots.

3.3.1. Surface plasmon resonance (SPR) and optical properties

AuQDs also exhibit surface plasmon resonance (SPR), a phenomenon in which conduction electrons on the nanoparticle surface oscillate in resonance with incident light. This leads to strong light absorption and scattering, with the resonance frequency being highly dependent on the particle size, shape, and local refractive index. The SPR properties of AuQDs are particularly sensitive to the surrounding environment, making them highly responsive to changes in the chemical or biological milieu. This feature is crucial for their use in sensing applications.

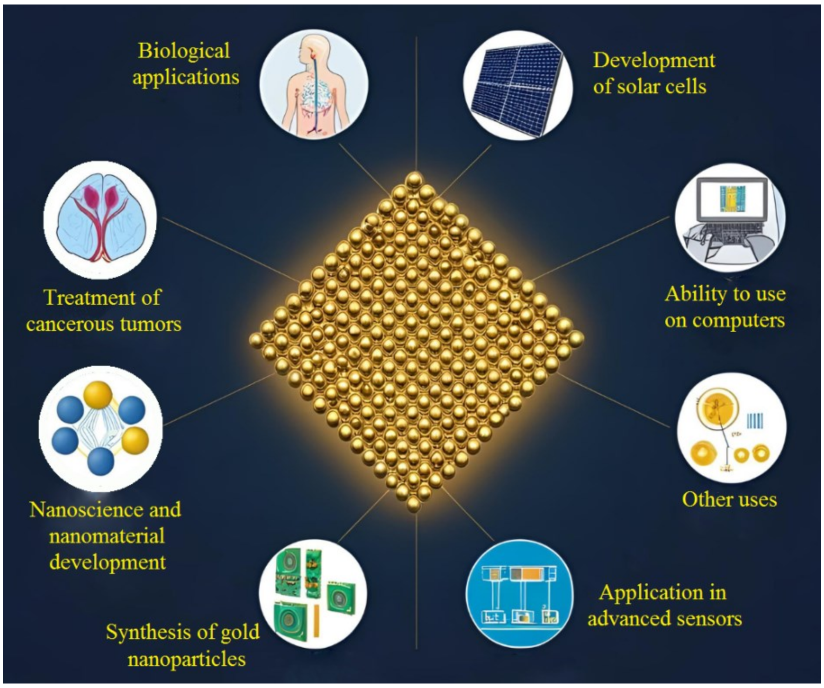

Figure 2. A schematic of some applications of gold quantum dots.

3.3.2. Sensing applications

The tunable optical properties and SPR effects of AuQDs make them excellent candidates for various sensing applications. AuQDs can be functionalized with specific ligands or biomolecules, enabling selective interaction with target substances such as proteins, DNA, or small molecules. This ability to alter their optical properties upon binding with specific targets forms the foundation of a wide range of biosensors. These sensors can detect subtle changes in the environment, making AuQDs ideal for real-time monitoring of biological or chemical processes. Additionally, their strong scattering and absorption properties allow the detection of even low concentrations of target molecules, enhancing sensor sensitivity. AuQDs can also be used in colorimetric sensors, where a visible color change occurs upon interaction with a target molecule, providing a simple and cost-effective detection method.

3.3.3. Optoelectronics

AuQDs possess unique electronic properties that are applied in various optoelectronic devices. Due to their discrete electronic states, AuQDs exhibit high quantum efficiency, making them valuable for light-emitting diodes (LEDs), solar cells, and other optoelectronic devices. The size-dependent emission properties of AuQDs allow the creation of light sources with specific emission wavelengths, improving the performance of optoelectronic components. For example, in solar cells, AuQDs can enhance light absorption and improve overall cell efficiency. Additionally, their photostability and non-toxicity make them a promising alternative to traditional semiconductors in optoelectronics. The unique properties of AuQDs, including their tunable optical absorption, surface plasmon resonance, and size-dependent electronic states, position them as key players in advancing the fields of sensing and optoelectronics, offering innovative applications for future technologies [35–37].

It is worth noting that the photo response mechanism of gold is also of interest in some of its applications. In this context, Mahmoud et al. [38] investigated the photo response performance of gold-titanium oxide and its importance. Chang et al. [39] also investigated the importance of this issue. In the study of Chang et al. [39], it was shown that although neodymium vanadate is used in some cases due to its strong absorption of ultraviolet light, its medical applications are weakened due to its weak absorption in the visible light regions that gold can compensate for. Also, some experiments showed that NdVO4/Au can act as a highly effective anticancer agent in tumor inhibition [39].

3.3.4. A review of the synthesis of gold nanoparticles

Gold nanoparticles are synthesized through a variety of physicochemical processes, which have advantages and disadvantages. One of the methods for synthesizing gold nanoparticles is the biological synthesis method [40]. This method is known as one of the suitable methods for producing nanoparticles due to its high efficiency. Nanoparticles produced by this method have high stability but may have biological hazards, and for this reason, other synthesis methods, such as green synthesis, have been developed [41]. Green routes using plant extracts as reducing and stabilizing agents for preparing gold nanoparticles are of interest [42]. Modified Nano-cellulose is also known as a promising material for extracting gold nanoparticles [43]. It is also possible to synthesize gold nanoparticles with models close to the Turkevich model, and in this model, trisodium citrate dihydrate and tetrachloroauric acid can also be used. In general, in some chemical methods, the synthesis of gold nanoparticles depends on the reaction time, acid concentration, and pH [44].

4. Integration of gold quantum dots with solar cells

4.1. Enhancing solar cell performance using gold quantum dots

With the continuous advancement of industries and the rapid growth of the global population, the demand for more efficient and sustainable energy sources has become increasingly urgent. Among various renewable energy options, solar energy has garnered significant attention, leading to the need for improving solar cell efficiency and generating higher energy outputs. To meet this demand, it is essential to enhance solar cell manufacturing techniques through methods that are not only safe but also minimize the environmental impact compared to traditional approaches, while achieving superior performance over conventional enhancement strategies. Scientific research and experimental findings indicate that the use of gold quantum dots has proven to significantly boost the performance of solar cells, delivering results such as higher power conversion efficiency, synergistic effects, and various other benefits. One of the promising solutions for improving the performance of solar cells lies in the incorporation of gold quantum dots, particularly in organic solar cells (OSCs). Organic solar cells have become a leading contender for renewable energy production due to their lightweight, flexible structure, low manufacturing costs, and ease of fabrication. However, these cells face the challenge of lower efficiency when compared to silicon-based solar cells. This is primarily due to their limited ability to absorb light across a broad spectrum, particularly in the ultraviolet (UV) region. Organic materials typically operate efficiently in the visible spectrum, but UV light remains largely unutilized in these cells, which leads to a reduction in the overall power conversion efficiency (PCE). In response to this challenge, researchers have employed two advanced technologies: gold quantum dots (AuQDs) and gold plasmonic nanoparticles (AuNPs). Gold quantum dots, with their extremely small size (less than 2 nanometers), possess unique optical and electronic properties. These properties enable them to absorb ultraviolet light and convert it into visible light, which is then absorbed by the active layer of the solar cell. This ability allows the solar cells to capture a wider spectrum of sunlight, enhancing their overall efficiency. In addition, gold plasmonic nanoparticles help generate strong localized electric fields, improving light absorption within the cell and facilitating the process of charge carrier generation (electrons and holes). To investigate the effects of these technologies, researchers tested three types of quantum dots that emitted blue (B-AuQDs), green (G-AuQDs), and red (R-AuQDs) light. These quantum dots, when combined with plasmonic nanoparticles, were strategically placed as an intermediate layer between the hole transport layer (PEDOT: PSS) and the active layer of the solar cell. The final structure of the solar cell included the following layers: a glass substrate coated with indium tin oxide (ITO), quantum dots, a hole transport layer with gold nanoparticles, an active layer, and an aluminum electrode. The key findings from this experiment demonstrated that the combination of green quantum dots and plasmonic nanoparticles achieved the highest performance. Specifically, this combination resulted in a 13% increase in power conversion efficiency (from 2.47% to 3.66%). This enhancement is attributed to the ability of the quantum dots to absorb ultraviolet light, convert it to visible light, and subsequently transfer it to the active layer, where it can be absorbed. Additionally, the plasmonic nanoparticles generated stronger electric fields, improving the energy transfer process and overall efficiency. The research also revealed that the combination of green quantum dots and plasmonic nanoparticles led to the most significant increase in short-circuit current (from 6.85 mA/cm^2 to 7.61 mA/cm^2). This improvement was due to a greater production of charge carriers and their more efficient transport within the device. Therefore, the enhanced short-circuit current (Jsc) stands out as one of the key advantages of incorporating quantum dots into solar cells. Moreover, the addition of quantum dot and gold nanoparticle layers reduced charge transfer resistance, signifying improved efficiency in the transport of electrons and holes from the active layer to the electrodes. For example, in cells containing green quantum dots and plasmonic nanoparticles, the charge transfer resistance (Rct) was reduced to 6.7 ohms, the lowest value recorded across all test samples. This reduction in resistance directly resulted from the synergistic effects of the quantum dots and plasmonic nanoparticles. The combination of quantum dots and plasmonic nanoparticles showed far superior performance compared to using either technology alone. The quantum dots enhanced the plasmonic effects of the gold nanoparticles by generating visible light, which, in turn, boosted the production of optical carriers and overall device performance. This phenomenon is referred to as the synergistic effect. The research demonstrates that pairing quantum dots with plasmonic nanoparticles can effectively address the challenges associated with light absorption in organic solar cells. The innovative design of this system not only improves power conversion efficiency but also enables the utilization of the ultraviolet spectrum, which was previously underused. The results highlight the potential of this technology for further development in the next generation of advanced solar cell applications [45–49]. Also, **Table 2** provides a general summary of the strengths, weaknesses, and efficiency requirements of solar cells [50–55].

Table 2. A summary of the efficiency, strengths and weaknesses of AuQDs in solar cells.

Increased efficiency	Reason for increasing solar cell efficiency	Ref.	Existing restrictions
In a study, solar cell efficiency was increased by 30%.	Integrating plasmonic nanostructures and enhancing light absorption intensity.	[51]	High manufacturing cost Recycling problems
Short-circuit current density and power conversion efficiency increase with the presence of gold quantum dots.	Localized surface the plasmon effect leads to enhanced light trapping.	[49]	There is a need for industrialization.
Using gold quantum dots increases efficiency by 104%.	Absorption coefficient of cadmium selenium quantum dots is improved by the addition of gold nanoparticles.	[53]	The limitations of using solar cells at night should be examined.
Increasing the efficiency of inverted organic solar cells	Gold quantum dots are used in inverted organic solar cells.	[54]	Construction limitations and high costs need to be considered.
JSC increases by 14.11% and PCE by 19.57%.	Due to the use of gold quantum dots with green fluorescent color (Green-AuQDs).	[55]	Limitations in size and the need for further investigation to build cells with large dimensions.

4.2. Future prospects

In the future, the development of gold quantum dot technology could open new horizons in the solar energy industry. Further research could focus on the following areas:

4.2.1. Optimization of production processes and cost reduction

Given the relatively high cost of gold quantum dot production, it is essential to develop cheaper and scalable production methods, such as simpler chemical methods or innovative techniques.

4.2.2. Material durability under various environmental conditions

The resistance of gold quantum dots to environmental factors such as humidity, heat, and prolonged exposure to radiation needs to be improved to be suitable for industrial and long-term applications. Results have also been observed that the use of gold quantum dots in this field increases cell durability [50]. The results also show that the greatest improvement in solar cell efficiency compared to reference cells exceeded 30% [51].

4.2.3. Application in next-generation solar cells

Research on integrating gold quantum dots with perovskite cells, hybrid cells, and thin-film solar cells can enhance the performance of these systems and optimize the use of the solar spectrum.

4.2.4. Energy efficiency improvement

By studying the interaction between gold quantum dots and other nanoparticles, such as silver nanoparticles or two-dimensional materials like Graphene, new synergies could be created to improve efficiency and reduce energy losses. Research has shown that the use of AuNPs/G6/GQDsx composites can play an effective role in enhancing the SERS response of solar cells [52]. In this regard, it is necessary to investigate the effect of the simultaneous presence of other quantum dots, such as gold and zinc sulfide, in the future.

One of the main challenges in the field of solar cells is their efficiency at night, which limits the efficiency of solar cells. In this regard, more research needs to be done in the future by researchers to be able to use solar energy during the dark period, and especially in rainy conditions.

Of course, it should be noted that the dimensions of the solar cell can play an effective role in energy storage. **Figure 3** shows two examples of solar cells coated with nanoparticles in different dimensions. Although **Figure 3a** shows smaller dimensions, it has the same efficiency as the example in **Figure 3b**, which is due to the application of nanoparticles and increased cell performance. Researchers can also do more research in this area in the future, and it is considered a suitable research area.

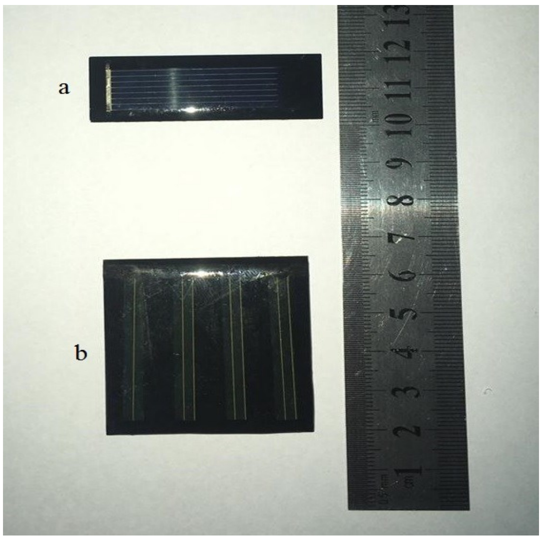

Figure 3. Examples of solar cells with different dimensions and different energy efficiencies (cells and image provided by the researchers of this article).

4.2.5. Applications in diverse fields

In addition to solar cells, gold quantum dots can be used in other fields, such as biosensors, advanced displays, and energy storage devices. Ultimately, the development of gold quantum dot technology could play a key role in achieving sustainable development goals and reducing the environmental impact of fossil fuel use. Given the growing global demand for energy and advancements in related technologies, a bright future is anticipated for quantum dots in the renewable energy sector. This technology could provide a scientific and practical solution, creating a new path for clean and efficient energy production on a global scale. Finally, it is proposed to use multilayer solar cells by applying different layers of gold Nano-dots similar to **Figure 4**. Such solar cells may be able to have higher efficiency. It should be noted that this is only a theory and needs further investigation in future research.

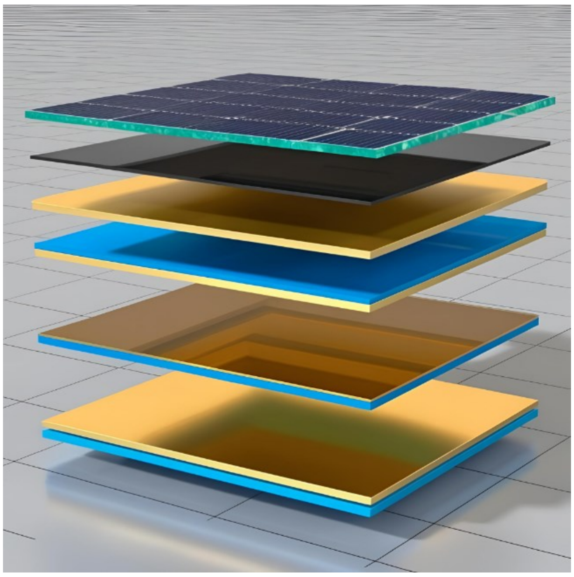

Figure 4. Schematic of multilayer solar cells as a theory for making cells with higher efficiency. This design has been suggested as a theory to researchers in future research, and whether or not the results are desirable requires future investigation.

5. Conclusion

The results of this study show that gold quantum dots (AuQDs), as one of the innovative technologies in enhancing the efficiency of solar cells, have significant potential to improve the performance of these systems. Due to their unique optical and electronic properties, such as ultraviolet light absorption and its conversion into visible light, as well as the generation of strong electric fields through plasmonic effects, these quantum dots can significantly enhance the efficiency of the solar light absorption and conversion process.

Laboratory studies have shown that combining gold quantum dots with gold plasmonic nanoparticles improved the power conversion efficiency of solar cells by up to 13% and significantly reduced charge transfer resistance. This combination also led to an increase in short-circuit current and better charge carrier generation, indicating effective interaction between quantum dots and plasmonic nanoparticles in boosting optical and electronic processes. Furthermore, the proposed structures in this study could serve as economic and efficient solutions for clean energy production in the future. This technology, by reducing dependence on traditional materials and increasing efficiency, represents an effective step toward achieving global environmental and economic goals.

At the end of this study, it is suggested that researchers in the future should make more efforts in the field of quantum solar cells. The use of gold quantum dots is a suitable solution to increase the efficiency of solar cells used in spacecraft. The use of carbon-gold composites can also be suggested in the cell.

In addition to the above suggestions, cell recycling methods can also be considered or the cell can be reused by adding quantum dots after a certain period. Quantum dots are a suitable solution to increase the efficiency of cells that have passed their lifespan and can be reused with this method. It is also finally suggested that multilayer solar cells with the application of gold nanoparticles be further investigated.

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