Recent QD-LSC Technology Development Report

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Abstract. Synthesizing an overview report of recent QD-LSC technology development with the introduction of Luminescent Solar Concentrators and Quantum Dots (QD-LSC) to focus on the development and advantages of LSC Quantum Dots, containing the main arguments and findings through literature review. Through the historical development, the current situation and advantages of various types of QD-LSC will be presented by tracing the development timeline. It will explain the underlying scientific principles of QD-LSC and discuss how quantum dots enhance luminescence. The detailed materials used in QD-LSC will display differentiated contributions to improved performance highlighting the significance of enhancing solar cell efficiency. The advantages include increased efficiency, versatility, cost-effectiveness and environmental influence. However, some challenges still exist, thus future developments will be proposed with potential advancements.

Keywords: QD-LSC; efficiency; solar; production.

1. Introduction

Living in current era where this generation witnessed unprecedented advances in technology and engineering marvels had given rise to the development of the nanomaterials to enhance the efficney, concurrently being environmental friendly. Over the past decades, notable advancements have been made in Luminescent Solar Concentrators (LSC), with a specific emphasis on incorporating Quantum Dots (QD) into these systems. This report is intended to offer a comprehensive review of the recent progress in LSC technology and the fundamental principles propelling its evolution. Simultaneously, it will display the advantages of QD-LSC with different types of materials to enhance the application efficiency and the development of luminescent solar concentrators (LSCs) and emphasize their potential enhancements through the incorporation of quantum dots (QDs).

1.1. What is LSC?

Luminescent solar concentrators (LSCs) are devices that utilize luminescent nanomaterials such as quantum dots (QDs) to absorb sunlight and re-emit at longer wavelengths. Then, these concentrated lights are directed into the solar cells for power generation. These concentrators provide an innovative method of utilizing solar energy [1].

According to Solar Energy Technology, A luminescent solar concentrator (LSC) is a device capable of absorbing and concentrating sunlight to produce electricity. Luminescent solar concentrators capture solar radiation over a large area. Subsequently, they convert this radiation into luminescence and direct it to a smaller target with a photovoltaic (PV) receiver."[2]

LSCs are (semi-)transparent plates that can absorb sunlight from a wide range of colors. Inside these plates, special luminescent emitters capture the sunlight and convert it to specific wavelength photons. These photons are bounced through the LSC device/plate regulated by the total internal reflection effect and concentrated on the edges of the LSC plate. At the edges of LSC, there are attached PV stripes, which can convert the concentrated photons into electricity. Given the flexibility and transparent characteristics of LSC devices, the application realm of the LSC-PV integrations can be largely broadened. In addition, through applying LSCs, the required utilization of PV devices can be significantly minimized, therefore reducing the production cost of the solar harvesting system. Additionally, the sunlight that goes through the solar panels is changed into wavelengths that are best for the cells to work efficiently.

1.2. The applications of LSCs

LSCs have various applications, especially in building integrated photovoltaic (BIPV) systems. Their cost-effectiveness and ability to function in diffuse light make them suitable for various settings, eliminating the need for expensive solar tracking equipment[1]. This subsection will display the typical applications and the roles of LSC. In summary, LSCs demonstrate their adaptability and potential across various domains, including urban development, architectural integration, and smart windows for buildings with enhanced solar energy harvesting and conversion. These applications underscore the versatility of LSC technology in advancing the utilization of solar energy across different sectors:

a. Urban Integration: LSCs have the potential to revolutionize the urban landscape by enabling the creation of visually appealing mosaic-like PV devices. These devices can seamlessly blend into the urban environment while efficiently capturing and converting solar energy, accelerating the adoption of solar energy in urban settings[3].

b. Built Environment: Within the built environment, LSCs can be incorporated into architectural elements such as windows and stained glass. With this LSC installation, not only the aesthetic appeal of buildings can be enhanced, but the windows/glass of buildings can be turned into on-site power-generation units[4]. Such innovation aligns with the principles of sustainable architecture, where structures serve as both functional spaces and renewable energy sources.

c. Smart Windows: LSC technology has found valuable applications in the creation of smart windows, which can intelligently control the amount of light entering spaces while producing electricity. These windows contribute to energy-efficient building designs, offering a comfortable and sustainable indoor environment. Smart windows represent an active element in building energy performance, providing multifunctional contributions to energy conservation through dynamic solar control and renewable energy production[5].

d. Solar Panel Efficiency: LSCs play a crucial role in improving the efficiency of traditional solar panels. By converting solar photons into the effective wavelength region for subsequent PV utilization, LSCs can enhance the overall performance of solar power generation systems[6]. This advancement is pivotal for achieving greater energy yield through solar energy production in a more cost-effective manner[17].

1.3. What is Quantum Dots(QDs) and QD-LSC?

Quantum dots (QDs) are nanoscale semiconductor particles with unique optical and electronic properties, such as tunable absorption and emission spectra. QD-LSC refers to a luminescent solar concentrator that uses quantum dots as luminescent materials to improve its efficiency and performance[1,2,3]. Quantum dots (QDs) are semiconductor nanoparticles that exhibit size and composition-dependent optical and electronic (optoelectronic) properties. Quantum dots are ultra-small, typically in the size range of 1.5 to 10.0nm. In recent years, quantum dot nanotechnology has successfully entered numerous electronic and biomedical industries. Quantum Dots (QDs) are semiconductor nanoparticles which exhibit size- and composition-dependent optical and electronic (optoelectronic) properties owing to their unique quantum confinement effect. QDs are ultra-small, typically falling in the size range between 1.5 and 20.0 nm depending Bohr radius of the materials[7].

In the field of solar energy collection, the concept of a quantum dot luminescent solar concentrator (QD-LSC) is at the forefront of innovation. Quantum dot LSCs represent a cutting-edge approach that combines the basic principles of luminescent solar concentrators (LSCs) with the unique characteristics of quantum dots (QDs), aiming to significantly improve the efficiency of solar energy collection and conversion. The core of quantum dot LSCs is quantum dots, which are tiny semiconductor materials with extraordinary light absorption capabilities. These tiny entities excel at absorbing broad-spectrum sunlight from visible light to infrared. The significance of quantum dots lies in their ability to effectively re-emit and absorb sunlight at longer wavelengths[8]. Hence, this unique feature enables QD-LCS to capture a wider range of solar radiation, including direct and scattered sunlight, for subsequent energy conversion in integrated photovoltaic cells.

1.4. The advantages of QD-LSC

QD-LCS has various advantages, including tunable absorption and emission spectra, high photoluminescence quantum yield, and potential for large-scale applications. These characteristics make them promising candidates for advancing solar energy conversion technology[5].

Solution processing is suitable for large-scale industrial production. QD-LSC possesses high photoluminescence quantum yields (PL QYs), which enhances the efficiency. For instance, as the size of LSC increases, the advantages of QC LSC over traditional QD LSC become particularly evident. It is predicted that the efficiency of QC LSC increases by more than four times in the case of window size (1m) devices[7].

Luminescent solar concentrators (LSCs) can serve as large-scale solar collectors for land and space photovoltaics. Due to their high emission efficiency and easily tunable emission and absorption spectra, colloidal quantum dots have become a new and promising LSC fluorophore. The spectral tunability of quantum dots also helps to achieve stacked multilayer LSCs, where enhanced performance is achieved through spectral splitting of incident sunlight[9].

2. Discussion

This section will demonstrate the working principles of QD-LSCs that how they are enhancing the efficiency and the recent development of them. It will also explain a variety of production processes and applications of LSCs. It outlines the working principle, production methods, and latest developments, with a focus on CdSe-based and ZnS-based QD-LCS. Production involves material selection, integration, design, photovoltaic integration, and customization for specific applications. Notable developments include the use of cost-effective chemical solution routes to synthesize CdSe quantum dots as well as ZnS quantum dots with high quantum yields, despite the challenges posed by their cleanliness. In addition, it also mentions CuInSe-based and perovskite-based QD-LCS, which have optimized optical performance and stability and can be used for integrated photovoltaic applications.

2.1. Working principles of QD-LSCs

The working principle of LSCs is to use luminescent substances to absorb sunlight and re-emit at longer wavelengths. QD-LCS enhances this process by using quantum dots, which can precisely control absorption and emission characteristics[10].

A luminous solar concentrator (LSC) is a transparent plastic or glass with an embedded QD emitter. The embedded quantum dots absorb sunlight and then emit photons, producing a glow that propagates and concentrates at the edge of the LSC device regulated by the total internal reflection effect. This is a very promising technology as it allows for large areas of virtual (semi-transparent) glass and relatively small areas of expensive solar cells. When the photons of sunlight come in, they are absorbed by the emitter and then converted into photons with lower energy. This lower energy photon propagates within the LSC. The main possible energy losses include escape cone losses and reabsorption losses. This process involves obtaining energy (photons), concentrating it at the edge of the LSC, and being captured by an integrated photovoltaic cell.

2.2. Production methods of QD-LSCs

Various production methods are applied to create QD-LCS. These methods include sol-gel spin coating, environmentally friendly synthesis methods and the use of different quantum dot components. The choice of method will affect the optical properties and performance of the obtained LSCs[11]. The production method of QD-LSCs involves several key steps designed to create these innovative devices for solar energy conversion. Here is an overview of the production process, including five steps:Selection of Luminescent QD Materials, Material Integration, Design and Shaping, PV Integration and Application-Specific Tailoring:

a. Selection of Luminescent QD Materials: The first step is to choose suitable QD materials. These QDs can efficiently absorb sunlight and re-emit it at longer wavelengths. The choice of QDs impacts the efficiency and spectral properties of the resulting QD-LSC.

b. Material Integration: The selected QD materials are then integrated into a (semi-)transparent matrix. This matrix can be made of various materials, including polymers or glass. The QDs are dispersed or doped within the matrix, ensuring even distribution to avoid agglomeration.

c. Design and Shaping: The QD-LSCs can be shaped into the desired geometry. This could be in the form of flat panels, thin films, or other geometries, depending on the specific application and design requirements.

d. PV Integration: PV cells are positioned around the edges or at the back of the LSC. These cells will convert the concentrated light into electricity. The integration of the PV elements is a critical aspect of the LSC design.

e. Application-Specific Tailoring: Depending on the intended application, the LSCs may be further tailored for specific needs. For example, in building-integrated PVs, LSCs may be designed to resemble windows or architectural elements, while in other applications, they may be optimized for different lighting conditions.

2.3. Recent developments of QD-LSCs

The production processes and their pros of two typical types of QD-LSCs will be highlighted, such as CdSe-based QD-LSC and ZnS-based QD-LSC with some other simple introduction of several different types of common examples of QD-LSC. It focuses on the latest development of quantum dot luminescent solar concentrators (QD-LCS). It focuses on economically and efficiently synthesizing CdSe-based QD-LSCs using chemical solution routes, as well as ZnS-based QD-LSCs with significant synthesis challenges. In addition, it also introduces QD-LCS based on CuInSe and perovskite, demonstrating stability and efficiency in large-area series systems, paving the way for integrated photovoltaic applications.

2.3.1 CdSe-based QD-LSC

Cadmium Selenide (CdSe) Quantum Dots LSCs are Luminescent Solar Concentrators that utilize nanoscale semiconductor particles made of cadmium selenide (CdSe) as the luminescent material. These quantum dots absorb sunlight and re-emit it at longer wavelengths, concentrating the light onto solar cells for enhanced energy conversion.

The study by using a chemical solution route [5] presents a cost-effective method for synthesizing CdSe QDs using a bottom-up approach. This method involves manipulating atoms and molecules in a chemical solution process, resulting in mono-disperse nano-sized particles. The process is low toxicity and cost-effective while maintaining ecological behaviour. Three solutions of CdCl2, H2O, 2-mercaptoethanol (ME), and sodium selenide anhydrous (Na2SeO3) were prepared in de-ionised water with magnetic stirring. The CdCl2 solution was poured into a spout balloon container, followed by ME and Na2SeO3 solutions. The resulting solution was washed multiple times with de-ionized water, centrifuged to remove impurities, and dried at room temperature. The process was repeated under atmospheric control and nitrogen gas. The researchers have previously proposed this procedure for synthesizing nanostructure materials.

"Compared with colloidal QDs, carbon dots (C-dots) exhibit excellent photo-stability, presenting a very promising solution to improve the long-term photo-stability of quantum dot-based LSCs."[12]. This study led by Liu has shown that the photo-stability of luminescent solar concentrators (LSCs) based on CdSe/CdS QDs can be enhanced using a tandem structure. A large-area thin film was fabricated and placed on top of the LSC, resulting in an external optical efficiency of about 1.4% under one sun illumination. The presence of C-dots significantly improved the photostability of the LSC under UV illumination. After 70 hours, the QD-based LSC with a protective C-dot layer retained 75% of its initial photoluminescence intensity.

2.3.2 ZnS-based QD-LSC

Zinc Sulfide (ZnS) Quantum Dots (QDs) are a notable category of nanostructures employed in Luminescent Solar Concentrators (LSCs). These QDs typically range in size from 10 to 100 nanometers, with their dimensions being on the order of the de Broglie wavelength of the electron. In terms of synthesis, ZnS QDs were synthesis using a method involving a mixture of CdO and StA in a molar ratio of 2:1. The mixture was heated in mineral oil until CdSt was formed, which was purified by recrystallization in toluene. Se powder was added to the CdSt MO solution, resulting in concentrations of 6.25mM Se and 12.5mM CdSt. The mixture was degassed, heated to 225°C, and cooled by injection of room temperature OlA. Excess CdStz and Se powder were removed by centrifugation, resulting in a yellow/orange solution with green luminescence. Zinc Acetate and S powder were added to the CdSe cores MO solution, resulting in a concentration of approximately 10.6 mM[13].

The ZnS QDs synthesized in MO were cleaned by increasing solution polarity with polar organic solvents. However, most polar solvents form a biphasic mixture, requiring a complex washing procedure. Optical characterization revealed a well-defined absorbance spectrum and a narrow PL peak, indicating a narrow QD size distribution. No ZnS nucleation occurred, and all ZnS formed is on the surface of the CdSe cores. The QY for these QDs ranged from 44 to 50%, and time-resolved spectroscopy yielded a lifetime value of 15.5 ns, typical for CdSe-based QDs. The synthesis of CdSe/ZnS QDs in MO proved to be very simple and easily reproduced, which consistently resulted in QDs with high QY. However, the cleaning of the QDs proved to be very difficult, which can be seen as the drawback of this type of QDs[13].

2.3.2 CuInSe-based QD-LSC, Perovskite-based QD-LSC and Perovskite-based QD-LSC

CdS quantum dot solar concentrator was prepared by sol-gel spin coating method. Optimize optical performance by changing annealing temperature. It was found that lower temperatures are preferred for preparing efficient QD solar concentrator systems[6]. Large area series connected LSCs were prepared using highly stable carbon dots (CD) and near-infrared emitting CuInSe2 − xSx/ZnS quantum dots. These systems exhibit stability and efficiency of 0.46% and 0.5%, paving the way for the construction of integrated photovoltaic (BIPV) equipment[1]. Perovskite materials, including perovskite-based quantum dots, show promise in LSC applications. These materials exhibit a maximum optical efficiency of 34.7%, highlighting their potential for further advancements in solar energy conversion[13].

3. Conclusion

LSC is promising because the Integration of QD into LSC has been recently investigated extensively. QD-LSC promising with unique advantages. This research direction is still ongoing with large potential. QD-LSCs hold the potential to be commercialized or industrialized for real-life applications. The integration of quantum dots into LSCs, such as CdTe, CdS, CuInSe2−xSx/ZnS, and perovskite-based QDs, has shown significant advancements in improving efficiency and stability[10, 11]. LSC Quantum Dots offer tunable properties, stability, and improved efficiency, making them attractive for various solar energy applications[13, 14]. Despite progress, challenges remain, such as the toxicity of certain materials. Future directions involve exploring eco-friendly QDs and addressing stability concerns to further optimize LSC Quantum Dot devices. The integration of quantum dots into luminescent solar concentrators holds promise for advancing solar energy technologies. Ongoing research focuses on overcoming challenges and optimizing device performance, providing a pathway for the future commercialization and widespread adoption of these innovative solar devices[15, 16].

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