Progress Of Advanced Quantum Dots and Their Applications in Quantum Dot Sensitized Solar Cells

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Abstract. Solar cell is a type of photovoltaic semiconductor panel that generates energy directly from sunlight. It is also known as a solar chip or photovoltaic cell. Solar cells are an important energy storage device and have drawn more attention lately because of the benefits of renewable energy, environmental friendliness, non-pollution, distributed power supply, scalability, and increased energy security. It is acknowledged that quantum dot sensitized solar cells, a type of solar cell that uses semiconductor quantum dots as sensitizers, can improve the photoelectrochemical performance of the cell. Quantum dots are essential in determining the performance of solar cells. As a result, identifying quantum dots with the ideal size, energy band structure, and surface properties is critical to the advancement of solar cell technology. This work briefly introduces the basic properties of quantum dots. The function of quantum dots in quantum dot-sensitized solar cells as sensitizers is then reviewed, as well as their mechanism for raising the efficiency of solar cells. Finally, this work discusses the prospects and challenges of using quantum dots in solar cells. Several research directions for further development in response to current problems were summarized: (1) exploring lead- and cadmium-free sensitizer technologies; (2) preparing photoanodes with high quantum dot loadings; (3) seeking for a new electrolyte that incorporates all solid configurations.

Keywords: Quantum dot sensitized solar cells; quantum dots; efficiency.

1. Introduction

The integrating of new materials has been proved to be a crucial aspect in the advancement of solar cell technology. Among these materials, quantum dots (QDs) have emerged as essential functional materials for modifying and enhancing the efficiency solar cells. This is mainly because of their distinctive characteristics, such as the size effect, high light absorption efficiency, broad band absorption, excellent light stability, and easy processing.

The QDs exhibit a notable size effect. They are nano-sized crystalline semiconductor particles with diameters ranging from 1 to 10 nanometers. They demonstrate quantum confinement effects, leading to remarkable changes in their optical and electrical characteristics. Consequently, QDs exhibit size-dependent bandgap properties, enabling them to absorb a broader spectrum of light.

QDs are more efficient at absorbing light than traditional semiconductor materials. Their exceptional light-absorbing capabilities are due to the phenomenon of multiple exciton generation. Unlike conventional solar cell materials, one absorbed photon can produce many electron-hole pairs (excitons) in QDs, thus increasing the efficiency of solar cells efficiently.

In addition, QDs have excellent light stability, enabling them to maintain their performance over long periods of exposure to sunlight. This durability ensures the longevity and reliability of quantum dot solar cells. In addition, they are easy-processing and compatible with different devices, which facilitate their integration into different types of solar cell technologies.

Given these properties, extensive research has been conducted to explore the applications of QDs in solar cells. These applications include thin-film solar cells, intermediate band solar cells, and sensitized solar cells using QDs. Each of these approaches uses QDs to improve specific aspects of solar cell performance, such as light absorption, carrier conveyance and charge separation.

Their properties and applications in solar cells are important for developing efficient and versatile solar energy technologies. QDs are promising candidates for improving performance of solar cells due to their size effect, high light absorption efficiency, broad band absorption, light stability, and easy processing. Continued research and exploration in this field is essential to unlock the full potential of QDs and pave the way for a sustainable energy future.

2. Quantum Dots

2.1. Basic Properties of QDs

The primary constituents of QDs are nanoparticles of group II-VI elements (CdS, CdSe, etc.) and group III-V elements (InP, etc.). Their sizes typically located within the range between a few nanometers and tens of nanometers. Depending on the material's composition, QDs can be classified as elemental QDs (such as C, Si QDs), compound QDs (such as CdSe QDs), and heterojunction or QDs with a core-shell structure. The size and structure of QDs closely relate to their properties [1,2]. The characteristics of QDs can be tunable by various sizes [3]. Size effect and surface effect are important properties of QDs.

2.1.1 The quantum size effect

The quantum size effect occurs, as the size of quantum dot gets closer to or less than the exciton hole radius. This transition results in the electronic energy level near the Fermi energy level changing from a quasi-continuous to a discrete energy level. For instance, CdS has an exciton hole radius of approximately 3 nm. When the CdS quantum dot particle size is less than 2.4 nm, its absorption and photoluminescence spectra clearly exhibit the blue-shift phenomenon. CdSe and InP are other QDs that also display quantum size effects [3]. The appearance of this effect is because of quantum confinement and the impact of electron-hole interactions. Research on the quantum size effect is essential for comprehending and utilizing the optical and electrical properties of nanomaterials.

2.1.2 The quantum surface effect

When a quantum dot reduces in size and most of its atoms are located on its surface, the quantum surface effect becomes apparent. This leads to the increase of specific surface area. Since the particular surface area is large for nanoparticles, the proportion of surface atoms occupied is much higher than that of bulk materials. Consequently, the number of undercoordinated, unsaturated, and dangling bonds among surface atoms increases. Due to their high reactivity and instability, the surface atoms of QDs readily bond with other atoms. This instability significantly impacts the optical properties of QDs made of graphene [4]. For instance, the surface state of these dots is controlled by their chemical groups. Upon exposure to UV light, some of the hydroxyl groups transform into carboxyl groups, which enhances the photoluminescence efficiency [3].

2.2. Properties of QDs: Optical and Electrical

2.2.1 Optical property

When a molecule absorbs photons with different wavelengths, its ground state electrons move to various excited states, resulting in absorption bands. After internal transitions and vibrational relaxation, excited electrons from the lowest vibrational energy level of the initial excited singlet state revert to the ground state, resulting in fluorescence emission. As it is shown in Figure 1, the Jablonski molecular energy level diagram provides a clear illustration of these processes. The fluorescence emission spectrum is not affected by the excitation wavelength because the electrons are evacuated to the excited state's lowest possible energy level before emission [5].

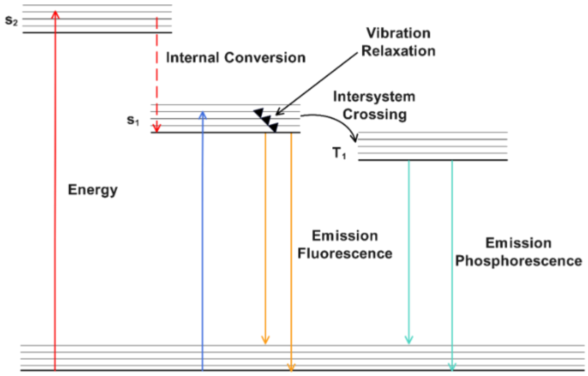

Fig. 1 Jablonski molecular energy level diagram.

Graphene quantum dots (GQDs) exhibit unique photochemical properties. Their fluorescence spectra are influenced by factors such as quantum size and spatial confinement, making them excitation wavelength dependent. GQDs possess luminescence bands that span from the deep ultraviolet to the near infrared [6]. Researchers can select specific irradiation wavelengths based on the area of interest, making GQDs useful for a wide range of optoelectronic applications. Additionally, GQDs display pH-dependent fluorescence emission and up conversion luminescence [7,8].

2.2.2 Electrical property

In recent years, researchers have become very interested in GQDs because of their photoluminescent properties. Electroluminescence, as opposed to photoluminescence, is a useful tool for studying GQD surface defects: because oxygen defects on the surface of GQDs can enhance their emission sites, the electrochemiluminescence effect is greater than that of GQDs after surface passivation [9,10]. In addition, a variety of parameters, including GQD size, physical conformation, defect concentration and chemical functionalization [11], can be modified to adjust the electronic properties of GQDs. It is reported that the main the differences in electrical characteristics of GQDs lie in electron-hole and electron-electron interactions.

These exceptional properties have made graphene quantum dots an attractive material of choice in recent years. Great application potential and research value can be seen in GQDs, as it is illustrated in Figure 2. GQDs possess a broad range of potential applications in numerous interdisciplinary domains, including photonics, electronics, catalysis, etc.

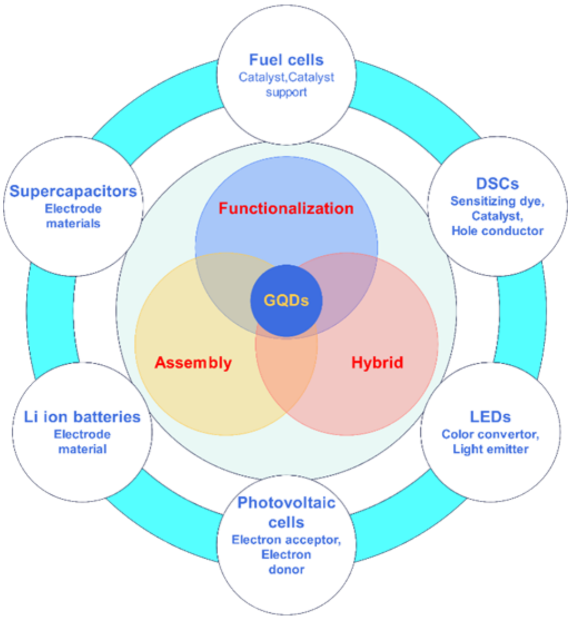

Fig. 2 Some potential applications of QDs.

3. Investigating the Use of QDs in Solar Cells

3.1. Quantum Dot Sensitized Solar Cells

Semiconductor QDs have garnered a lot of attention recently as a possible material for solar energy conversion due to their outstanding optical and electrical features. Quantum dot sensitized solar cells (QDSSC) are very promising solar cell devices.

3.1.1 Structure of QDSSC

A QDSSC is composed of three components: the photoanode, electrolyte, and counter electrode. Figure 3 illustrates their structural layout.

The photoanode is composed of conductive glass (FTO), oxide films (such as ZnO, SnO_2, and TiO_2), and quantum dot sensitizers [12]. Better light transmission, low resistance, stability, and non-reaction with electrolyte are among the benefits of conductive glass. Broader energy bands in wide-bandwidth oxide semiconductors allow for improved electron collection as an electron transport layer. These semiconductors also serve as a pillar and enhancer for quantum dot sensitizers. Numerous research groups have conducted extensive studies on photoanodes. By changing the structure of the electron transport layer, the ability to trap light and the number of QDs attached were increased [13]. The sensitizer is crucial as it captures photons and stimulates electrons from their ground state. To achieve high photoelectric conversion efficiency in QDSSC, the quantum dot sensitizer must have a high absorption coefficient and a band gap that corresponds to sunlight. One option is to use planned and synthesized co-sensitized QDs, such as CdTe/$Zn_xCd_{1-x}S$, $CuInSe_2$, etc [13]. These QDs can inject electrons more quickly and absorb a wider range of light. They can be binary, ternary, or quaternary in nature.

In recent years, during the conversion of QDs solar cells into photovoltaic cells, a significant number of valence band holes have been produced by QDs. This increase in hole density of electrons gradually facilitates the combination of excited state electrons with holes, thereby reducing photovoltaic efficiency. The electrolyte conducts charge through the external circuit to enable the flow of electricity. In addition, the valence band perforations of the QDs facilitate the circulation of current, thereby improving the conversion efficiency. Because it can stable CdS QDs, polysulfide electrolyte is the most often utilized electrolyte in QDSSCs [14].

The counter electrode in a QDSSC primarily functions to catalyze the transition from the oxidation to the reduction electrolyte. Furthermore, the catalytic activity of the counter electrode can affect the photoelectric conversion efficiency of the QDSSC. Currently, most counter electrodes of QDSSCs are made of metal sulfides, with copper sulfide being the most extensively studied due to its high catalytic activity for the electrolyte reduction reaction [15].

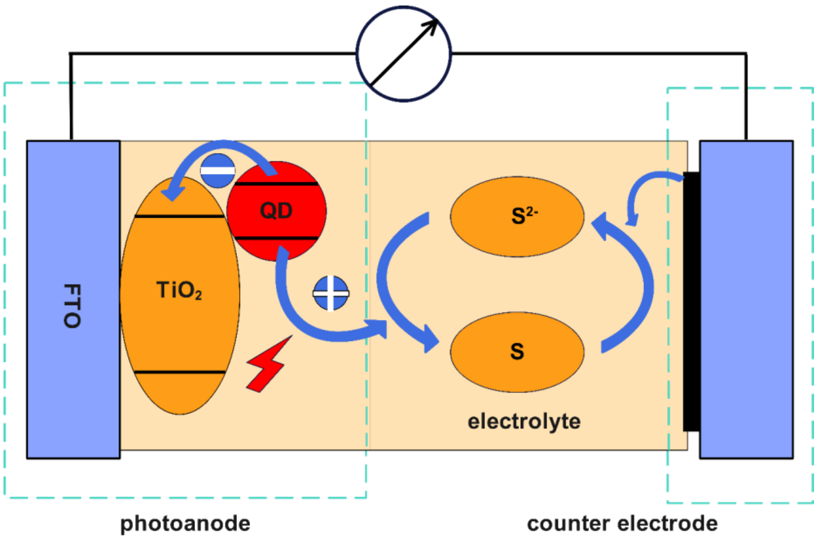

Fig. 3 Schematic illustration of the device structure of QDSSC.

3.1.2 Basic principles of QDSSC

Figure 4 shows the operating mechanism of the QDSSC. When sunlight strikes one side of the photoanode, CdS/CdSe quantum dots absorb photons and store energy. The ground state is induced to excited state, thus forming a pair of electrons and holes [13].

The process of charge separation is achieved by rapidly injecting electrons from the conduction band (CB) of QDs into the electron acceptor of the metal oxide (TiO_2). The electrons then travel through an external circuit from the transparent conductive oxide substrate to the counter electrode via the TiO_2 mesoporous film [16].

The S^{2-} reducing species in S_n^{2-}/ S^{2-} systems effectively consumes the photogenerated holes that accumulate at the TiO_2/QDs interface, facilitating the regeneration of QDs. The electrolyte contains reversible redox pairs, with the oxidized S_n^{2-} material in the electrolyte easily converted to S^{2-} by collecting electrons at the electrolyte interface. The electrolyte contains reversible redox pairs, with the oxidized S_n^{2-} material in the electrolyte easily converted to S^{2-} by collecting electrons at the electrolyte interface. The electrolyte contains reversible redox pairs, with the oxidized S_n^{2-} material in the electrolyte easily converted to S^{2-} by collecting electrons at the electrolyte interface. This process is frequently called the diffusion process or the redox reaction [17]. The electrolyte in the battery undergoes oxidation when it receives holes at the photoanode. This redox reaction occurs in close proximity to the two electrodes, forming a closed circuit within the battery [13].

3.2. Mechanism of Quantum Dots to Enhance the Efficiency of Solar Cell

The QDSSC is one of the newest types of solar cells. It has become a popular research topic due to its easy-processing and high energy conversion efficiency. traditional solar cells can be coated with quantum dots to enhance their efficiency through the down-conversion effect [3].

Spectral downshift is a process by which a single photon is transformed into a low-energy photon, according to Stokes' law. The wavelength shift resulting from this process is known as the Stokes shift. Spectral downshifting is similar to quantum clipping. While the conversion efficiency of the quantum clipping process exceeds 100%, it is still comparable to quantum clipping. The conversion efficiency of solar cell can be effectively increased by enhancing the sensitivity to short-wave photons [18].

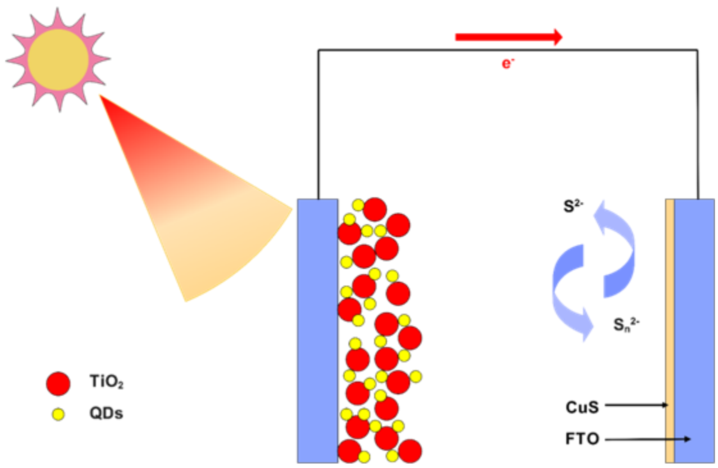

Fig. 4 Schematic diagram of the mechanism of QDSSCs.

3.3. Prospects and Challenges

In recent years, research on the application of inorganic luminous quantum dots in LED displays, photodetectors, solar cells, and other applications has gained significant attention due to their high luminescence performance, large degree of defect tolerance, wide bandgap adjustment, and other excellent optoelectronic properties. QDSSC have demonstrated an increase in performance, with a photoconversion efficiency greater than 13% [19]. Unlike previous QD solar cell topologies, Pb and Cd-free sensitizers have been claimed to achieve high efficiencies for QDSSC. Future challenges for this technology, which will further improve the performance and stability, are mostly focused on creating new electrolytes with all-solid topologies and developing techniques to create photoanodes with exceptionally high QD loading.

4. Conclusion

A solar cell has gained significant attention. Quantum dots possess unique properties, including tunable energy band structure. Quantum dots are ideal candidate for solar cell modification because they can absorb certain wavelengths of light and facilitate charge transportation.

The focus of QDs in solar cells is to improve their photovoltaic conversion efficiency and stability. Controlling the size and morphology of quantum dots can optimize their sensitization and carrier transport properties, leading to improved photoelectric conversion efficiency of cells. Additionally, improving the stability of QDs to the electrolyte can extend the lifetime of the cell. Therefore, it is important to select QDs with ideal size, energy band structure, and surface properties.

QDs are crucial components in quantum dot sensitized solar cells. They serve as light-absorbing materials that can expand the light-absorbing range of the cell. Furthermore, QDs can prolong the lifetime of electrons and holes, and enhance the efficiency.

In conclusion, QDs are essential for the optimal functioning of solar cells. To enhance their efficiency, some challenges still need to be faced. Firstly, it is necessary to develop sensitizer technologies that are free of lead and cadmium. Secondly, methods must be developed to prepare photoanodes with high QDs loading in order to improve photoelectric conversion efficiency. Additionally, new electrolytes suitable for all solid-state configurations, with high thermal, mechanical and chemical stability, must be found to enhance battery safety and stability.

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