Review Article

Recent Advances in the Development of Quantum Materials for the Construction of Solar Cells: A Mini Review

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Abstract

Solar cells are one of the most important equipment's in the field of clean and novel energy that can be used without chemical pollution. Solar cells are very valuable equipment that by using them, in addition to reducing environmental pollution, can benefit from clean energy. Solar cells are generally used in various industries, including aerospace, clean energy and even transportation. In the meantime, increasing the efficiency of solar cells is of great importance, and the development of quantum science has made a significant contribution to this issue. The use of quantum dots containing different materials such as graphene, carbon, gallium, lead and similar materials can increase the efficiency of solar cells from 3 to more than 50% on average. Also, the power conversion efficiency in solar cells developed with quantum dot technology reports from 1 to more than 15% improvements compared to conventional solar cells. In this research, to summarize the latest achievements in this field, an overview of the importance of quantum dots about the development of solar cells has been done.

Keywords: Quantum Dots, Solar Cell, Quantum Materials, Graphene, Power Conversion Efficiency.

1. Introduction

Quantum materials are one of the new types of materials that have been considered in the development and manufacturing of sensitive parts [1-3]. One of the notable points is that most of the materials of interest in the field of quantum material are inorganic compounds or alloys. Almost all quantum materials are sensitive to chemical impurities and defects [4]. One way to develop quantum materials is to use Quantum Dots (QDs). Quantum dots are semiconductor crystals with a diameter of 2 up to 10 nm, which have special properties in the optical and electrical fields and these materials behave differently from larger particles due to their quantum mechanical properties [5,6]. Quantum dots on surfaces form a super-lattice if they are doped together. These super-lattices act as artificial materials and show special optical and electronic characteristics [7]. This feature has caused quantum dots to be considered in various applications such as lasers [8], sensors [9] and solar cells [10]. Fig. 1. shows an overview of the uses of quantum dots in different sciences. Nowadays, due to the many limitations in energy, it is very important to pay attention to solar cells. A solar cell is an electronic device that, after receiving the sun's radiation, directly converts the sun's energy into electricity using the photovoltaic effect [11].

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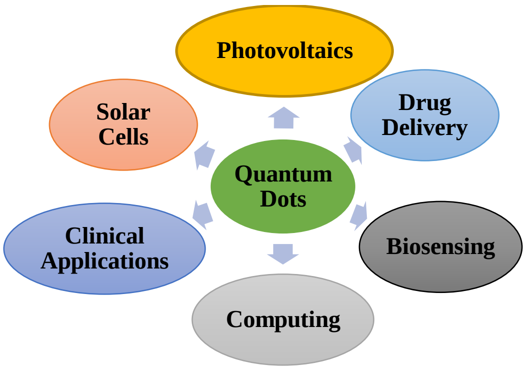

Fig. 1. Uses of quantum dots in sciences [5].

Many materials are involved in the development of solar cells. Crystalline and amorphous silicon-based solar cells have led the solar industry [12].
The use of Cadmium telluride solar cells is also considered [13]. Also, the development of indium copper solar cells has attracted the attention of researchers [14]. However, there are limitations in the field of energy efficiency in the development of solar cells, which can be reduced by developing quantum dots and identifying optimal quantum materials.
In the continuation of the current research, the new cases of using materials and quantum dots in the development of solar cells will be reviewed.

2. Quantum Materials for Solar Cells

Quantum materials are considered as one of the new materials for the development of solar cells. In the meantime, special attention has been paid to various types of quantum dots, including graphene, gold, CdS and similar materials, which will be referred to in a categorized manner in the following research.

2.1. Graphene-Based Quantum Dots

Graphene is one of the important materials in the field of quantum dots development. So far, researchers have done many research in the field of solar cells, including the development of graphene dots in silicon-based solar cells, dye-sensitized cells, and organic solar cells. In this field, one of the notable points is the high gain of Si-diodes in solar cells, which have a longer lifespan, but the use of graphene sheets can improve the performance of these diodes [15,16]. However, the applications of graphene quantum dots are not limited to this. Das et al. [17] investigated the realization of graphene-based quantum dot solar cells. In this research, quantum dots were created using several layers of graphene sheets. The results showed that the creation of new conditions can change the efficiency of the e-p pair between 90.6% to 95.2%. In another research, Yan et al. [18] investigated the effect of graphene dimensions as a quantum material in solar cells. Generally, it is not common to use graphene with large dimensions because there is a possibility of graphite accumulation. However, the research results of Yan et al. showed that by using suitable solvents, black graphene particles can be used as the final quantum compound, which leads to improved solar cell performance.
Another application of quantum dots is in the development of perovskite solar cells. The perovskite solar cell is a type of solar cell that is often made of an organic-mineral hybrid and lead or tin halide. Perovskite materials such as methyl-ammonium lead iodide or the mineral cesium lead iodide have a quick and cheap manufacturing process [19,20]. In this regard, Zhu et al. [21] investigated the effect of graphene quantum dots on this type of solar cells. Their results showed that the presence of an ultra-thin graphene quantum layer in the solar cell increased the efficiency of the cell from 8.81 to 10.15% and also the presence of this ultra-thin layer increases the speed of electron extraction. About graphene quantum dots, one of the most important cases is the use of synthesis processes. Synthesis is one of the main processes in the development of solar cells. In this regard, Teymourinia et al. [22] research showed that the use of the graphene quantum dots synthesis process increases the JSC rate in solar cells by 21%. The results showed that the presence of oxygen can lead to the formation of PbI_2 and the effect of transformation of ZnO. By synthesizing graphene quantum particles on the surface of the solar cell, this transformation is prevented, which increases the efficiency by 17% [23]. Finally, according to the research of Zhao et al., the application of graphene quantum dots synthesis is not limited to solar cells and is also used in the field of drug delivery materials [24].
In line with graphene quantum dots, other research has been done. The results of Li et al.'s[25] research showed that graphene quantum dots are important as hole transport layers (HTL) in organic photovoltaic cells. This issue creates a power efficiency of 3.51% and 6.82% in solar cells. Notably, Graphene quantum dots (GQDs) are a new class of fluorescent reporters promising various novel applications [26]. Also, graphene quantum dots have been considered in tunable photoluminescence properties [27].

2.2. Carbon-Based Quantum Dots

Another extensive research in the field of solar cells is the development of carbon quantum dots. Carbon has the same conditions as graphene, but the properties created are different. There is one major difference between carbon and graphene. The most difference is, the graphene is a single thin layer 2D film, and whereas the Nano-carbon is a thin film rolled as 3D tube. This difference has caused their classification to be separated. Among various carbon-based nanostructures, carbon quantum dots have desirable properties, including good conductivity, low toxicity, favorable optical properties, and simple synthesis methods [28,29].
Various research has been done in this regard. As pointed out by Kim et al. [30] various CQDs have been used or doped into the photo-anode, counter electrode, hole transport layer (HTL), and electron transport layer (ETL) of dye-sensitized solar cells (DSSCs), organic solar cells (OSC), as perovskite solar cells (PSCs), and other PV cell configurations. Also, the importance of carbon quantum dots was noticed by Huang et al. The results of their research on CdS-sensitized solar cells have shown that the presence of carbon quantum dots can improve the cell's photovoltaic performance. In this research, the effect of the presence or absence of carbon quantum dots in solar cells has been investigated. The results of Table. 1.denote that the presence of a combination of CQDs and CdS QDs increases cell productivity [31].

Table. 1. Power conversion efficiency and FF factor in solar cells [31].

Type of QDs	PCE	FF
With CQDs	0.265	0.400
With CdS QDs	0.430	0.370
Both CQDs &CdS QDs	0.616	0.410

Vercelli et al.'s [32]. research results have summarized the positive effect of carbon quantum dots on solar cells. Also, the effect of the presence of carbon quantum dots in perovskite solar cells has been investigated [33].

The results showed that comparing cells without quantum dots with cells with quantum dots, the power conversion efficiency (PCE) increased from 16.57% to 20.44%. Also, the results have shown that the superior fill factor has also increased from 70% to 75% [33].

Similar results were also reported by Guo et al. [34] that the synthesis of carbon quantum dots leads to a 0.11% increase in power conversion efficiency (PCE) in solar cells. It should be noted that the synthesis of carbon quantum dots in this research was done from natural materials such as bee pollen. This method is known as green synthesis and plays a role in preserving the environment.

2.3. PbS Quantum Dots

Lead sulfide (PbS) is one of the types of colloidal quantum dots (CQD), which are among the most important materials in this group [35,36]. Colloidal quantum dots, including lead sulfide, have attracted the attention of researchers for reasons such as tunable band gap properties, multiple exciting generation(MEG), and near-infrared [37].

In this regard, Kumar and et al. [38] conducted research on PbS quantum dots. Their modeling results showed that the presence of PbS quantum dots can improve the performance of solar cells. Also, another research was done by Ding et al. The results of this research showed that PbS quantum dots exhibit a power conversion efficiency of 15.45% [39]. Of course, it should be noted that research in this field can be expanded with the presence of graphene quantum dots and lead sulfide.

The studies of Lu et al [40] also consider the use of solar cells based on colloidal quantum dots to be important. However, their development may be limited due to the performance gap between colloidal solar cells and conventional structures. In this regard, Lu et al. investigated the effect of PDTPBT polymer as a buffer layer, which showed that the power conversion efficiency increases by 8.45% with the use of this polymer.

Similar to this issue was also seen in the research of Sukharevska et al. One of the problems of making solar cells based on PbS quantum dots is the instability of the colloidal, which prevents the construction of large size solar cells.

To solve this problem, $CH_3NH_3PbI_3$ was used as an auxiliary material, which has led to the stability of colloidal materials, and by using this method, the efficiency of the solar cell with PbS quantum dots increased up to 8.7% [41]. Also, to increase the efficiency and improve the capability of lead sulfide quantum dots, Hu et al used Ag doping in solar cells containing lead sulfide quantum dots. In this condition, the power efficiency increased from 9.1% to 10.6% [42]. Finally, the importance of the development of PbS quantum dots has been emphasized in the research of Blachowicz et al [43].

2.4. Gallium Quantum Dots

Gallium is another element involved in the development of quantum dots compounds. The development of various quantum dots such as GaN [44], GaAs [45], and GaAl [46] and the same has been investigated by various researchers. In this regard, Benyettou et al investigated solar cells with gallium quantum dots. Their results showed that the presence of GaSb quantum dots can improve the performance of solar cells. The presence of GaSb/GaAs quantum dots increases the efficiency of the solar cell by to 36.3% [47]. Also, the application of InGaAs quantum dots in high efficiency solar cells has been investigated [48]. In a similar research, it was found that the presence of InAs quantum dots in the solar cell along with the inhomogeneous structure of InGaP/GaAs increases the absorption range of the solar cell, and as a result, the efficiency of the cell increases. The addition of the aforementioned materials and the quantum dot layer increases the absorption edge of the solar cell [49]. Also, the use of InAs/GaNAs quantum dots in direct doping can lead to an increase in photocurrent by optical transitions. The research results have shown that the presence of quantum dots leads to the improvement of the open circuit voltage from 0.73 to 0.90 V. In addition, a 29% increase in efficiency was observed in solar cells containing quantum dots [50]. It should be mentioned that there is also research in the field of indium gallium (InGaN) quantum dots, which covers the range of ultraviolet to infrared light. In this approach, in an optimal molar fraction of indium and gallium, quantum dots can absorb wavelengths between 142 and 1565 nm. Indium gallium compounds are useful for a wide range of solar cells [51].

2.5. Gold Quantum Dots

Metallic gold nanoparticles (Au NPs) with multilayer gold atoms are used for various applications. Some of these applications include plasmonic, chemical, medical and meta-material applications [52]. New research also shows the importance of developing gold nanoparticles as new quantum dots in the development of solar cells.

In a part of Khalifa et al.'s [53] research, the effect of the presence of gold nanoparticles on the solar cell was investigated. In this research, in addition to the usual tests, XRD and TEM were also used to check the properties. The results showed that the structures of gold nanoparticles on the cell are polycrystalline and gold nanoparticles increase the efficiency of the solar cell by 15%. A similar issue was investigated by Phetsang et al.

The results showed that compared to the reference cells, the presence of quantum gold nanoparticles increases the photovoltaic efficiency, as a result of which the short-circuit current density (Jsc) and power conversion efficiency increase.

In the research results, it was found that the best synergistic effect is created after creating a gold quantum dot layer with a green-emitting and an HTL containing Au nanoparticles, which increases the highest improvement by 13% [54].

Similar results have also shown that the presence of gold quantum dots (AuQDs) leads to an increase in solar cell power conversion efficiency by 16% [55]. It is noteworthy that AuQDs are among novel materials and are not only used in the field of solar cells. One of the applications of quantum gold nanoparticles is in nucleic acid detection.

Nucleic acids are large biomolecules that are crucial in all cells and viruses [56]. Besides this issue, the use of gold quantum dots is also useful in the detection of thiocyanate.

The complete absence of thiocyanate or reduced thiocyanate in the body is damaging to the human host defense system and for this reason, it is considered an important biological substance [57-59]. According to this issue, the applications of gold quantum dots are useful in the detection of thiocyanate [60].

2.6. CdS Quantum Dots

Cadmium sulfide quantum dots are a common type of nanoparticles that play a key role in core-shell quantum dots [61]. These materials are generally used for biomarkers and solar cells.

There are various methods of synthesizing and applying CdS quantum dots, among which the sol-gel method can be mentioned. In this regard, the results of Sonker et al. research showed that by using the sol-gel method, the necessary characteristics are created on the solar cell. Also, due to the application of the quantum layer of cadmium sulfide, the efficiency increases by 72% compared to the original solar cell [62].

As seen in the previous section, solar cells based on Ga quantum dots are one of the prominent cases in this field.

In this regard, in research, the results indicated that the use of cadmium sulfide (CdS) quantum dots creates 18.9% more power conversion efficiency compared to GaAs quantum dots [63]. Also, the size effect of cadmium sulfide quantum dots has been investigated.

This matter is of great importance. Table. 2. denote the comparison results of CdS quantum particle size and efficiency. As it is known, with the increase in the size of the quantum particles, there has been a relative increase in efficiency [64]. Therefore, choosing the right size is very important.

Table. 2. Comparison results of CdS quantum particle size and efficiency [64].

CdS Particle Size (nm)	3.210	3.400	3.700	4.010	4.400
Solar Cell Efficiency %	0.150	0.240	0.370	0.420	0.480

In research, the importance of developing solar cells with combined quantum dots has been investigated. In this regard, in a research by Mao et al., investigated the simultaneous application of quantum dots of lead sulfide and cadmium sulfide on the surface of the solar cell. The application of lead and cadmium quantum dots prevents the excessive growth of lead quantum dots, which makes the solar cell more efficient. Also, the mutual penetration of both sulfides causes high density defects to be deactivated, which increases the efficiency of the cell again. Finally, the results showed that in TiO_2 solar cells sensitized to the mentioned two sulfides, the efficiency of the cell increases 5 times [65]. This issue can be considered in future research and for this purpose compounds such as graphene/PbS should be investigated.

2.7. InP Quantum Dots

Indium Phosphide (InP) quantum dots are among the colloidal quantum dots that are used in the development of solar cells and transistors [66]. Indium phosphate quantum dots have a suitable band gap and a high absorption coefficient, and on the other hand, their inherent toxicity is less compared to materials such as cadmium and lead, which makes this material more useful [66-67].

With the aim of developing InP quantum dots, various researches have been carried out. In a research, Yin et al investigated the effect of applying InP quantum dots on the TiO_2 layer. In this research, a 10 nm layer of QDs was created on the surface. The results of this research after various tests showed that the solar cell efficiency increases up to 19.2%, which is a significant amount without the presence of Pb and Cd quantum dots [68]. Similar results of increasing solar cell efficiency have also been shown in other researches, which increase up to 13.8% efficiency [69].

Also, in a comprehensive research, Harabi investigated the synthesis of InP quantum dots. In this research, InP quantum dot synthesis by hot injection method was used as a basis for photo electrochemical application. According to the results of the aforementioned research, the results of XRD analysis showed that the presence of InP QDs on the surface is confirmed. Also, hot injection method can be used as a new method [70].

Finally, the combined development of quantum dots is still of interest. In the previous sections, explanations were given about carbon quantum dots, and in this regard, Chen et al investigated the effect of the simultaneous use of carbon and indium phosphide quantum dots. In this research, the created system consisting of CQDs and InP QDs was used to study photo-catalytic hydrogen production from hydrogen sulfide (H_2S), and the results showed that this system can be 2.1 times more efficient than the normal state. Of course, it should be noted that some photo-catalytic reactions can also increase surface oxidation [71]. It is worth mentioning that in the multiple use of quantum dots, the use of AgIn and CdS quantum dots has been considered. In this research conducted by abate et al., an outer shell of ZnS quantum dots was created on the AgIn surface. This showed that by creating a core/shell/shell (AgInSe/CdS/ZnS) structure, the efficiency of the solar cell can be increased up to 6.27% compared to the normal state [72].

2.8. Ag_2S Quantum Dots

Ag_2S quantum dot is a semiconductor with narrow band-gap, broad light absorption, photovoltaic effect and photoluminescence. This material has a special chemical stability, which is one of its desirable features. Behaviors such as high photovoltaic properties and chemical stability have raised this material as one of the candidates for manufacturing solar cells, sensors and lasers [73,74].

In this regard, Suarez et al investigated solar cells sensitized to Ag_2S. The results showed that the best power conversion efficiency in these solar cells increases to 1.70%. Also, these solar cells are a broadband sensitizer in the structure of the cells [75].

It is worth mentioning that one of the methods of applying Ag_2S quantum dots on the surface is the SILAR method (Successive Ionic Layer Adsorption and Reaction). In this method, the number of repetition cycles is important.

For this purpose, the effect of this issue has been investigated in are search. The summary results denoted at Table. 3. By increasing the number of SILAR cycles, the efficiency of the solar cell first increases and then decreases [76]. This issue indicates that researchers should identify suitable SILAR cycles in their research.

Table. 3. Efficiency data of Ag_2S-QD solar cells with different SILAR cycles [76].

Quantum Dots (SILAR cycles)	FF %	Efficiency %
Ag_2S (3)	38.1	0.430
Ag_2S (4)	47.4	0.700
Ag_2S (5)	36.8	0.510
Ag_2S (6)	29.8	0.330

It should be noted, the duration of the sensitizing processes of quantum dots is important, especially in Ag_2S QDs. In a research, the researchers investigated this issue and the average time of sensitizing was up to 5 hours.

The results showed that in this period of time, the efficiency of the solar cell first increases and then decreases, and the highest efficiency of photoelectric conversion increases to 3.97%. Sensitization for more than 2 hours lowers the functional conditions of the cell, which was reported to be the reason for the augmented trap sites in the Ag_2S layer [77]. Of course, it should be noted that in future researches, times of more than 5 hours can be investigated in the layers and the results reported.

Finally, other research also reported the positive effects of silver quantum dots. In the research of Ranjitha et al., the doping of silver quantum dots leads to an increase in power conversion efficiency up to 1.48% [78].

Also, the presence of a combination of CdS and Ag_2S QDs can increase the solar cell efficiency by 2.66% [79]. Finally, it should be mentioned that apart from the issue of solar cells, Ag_2S quantum dots can be exploited in the development of biological imaging [80].

2.9. Other Quantum Materials

There are other materials for quantum dots that are briefly discussed in this section. Research has also been done in the field of solar cells based on SnS quantum materials. In a research, Yang et al. showed that the presence of SnS quantum dots can increase power conversion efficiency by 13.7%. Also, these solar cells have better stability in the air and the results have shown that the cell can maintain its performance up to 1000 hours without change [81]. In a research, it has been reported that the presence of SnS layers varies from 3 to 5 nm, which improves cell efficiency [82]. Also, the previously mentioned SILAR process is used to create SnS quantum dots on the solar cell [83].

Zinc sulfide (ZnS) is also one of the other important quantum materials in the development of quantum dots in solar cells. The results of various researches have shown that the use of ZnS quantum dots can increase the efficiency of the cell by more than 7% [84,85]. Also, different concentrations of poly-vinyl-pyrrolidone (PVP) are used for the synthesis of ZnS, which has been of interest in some research [85,86], but it is necessary to pay attention to parameters such as synthesis time and the use of combined quantum dots.

Also, quantum dots containing copper are also being considered today. Copper is of interest due to properties such as high electrical conductivity. The results have shown that the presence of copper along with Zn/In quantum dots can increase the efficiency of the solar cell compared to the neutral state.

The highest amount of power conversion efficiency in these solar cells increases to 12.57%, which is one of the highest reported numbers [87].
Also, the use of copper in InSe quantum dots reported similar results. In this case, PCE reported an increase of 8.1% [88]. Since copper is a naturally harmless metal, the development of solar cells containing copper should be more on the agenda of researchers.

3. Conclusion

Quantum materials are one of the new sciences that create special features in the structure of different materials. Meanwhile, the development of solar cells with quantum dots is very important. Increasing the efficiency of solar cells is of great interest due to energy crises. In this regard, in the current research, the subject of recent achievements in the field of quantum dots in solar cells has been considered. In general, the results are categorized as follows:
1. The development of solar cells with quantum dots from 1 to more than 20% can lead to an increase in efficiency.
2. Among the different materials, the use of graphene is of interest due to its special features.
3. The development of quantum dots of lead sulfide and cadmium simultaneously increases the efficiency of the cell.
4. The development of sulfide quantum dots along with carbon quantum dots needs further research in the future.
5. Quantum dots of InP and Ag_2S are among the materials that have been considered by researchers, and their further development can create desirable characteristics in solar cells.
6. The use and exploitation of gold quantum dots can be used in solar cell applications, which requires more attention.
7. Copper is one of the materials that is effective in the development of quantum dots and due to the important feature of being non-toxic, it can be a suitable material for the development of solar cells.
8. The development of solar cells with quantum dots in summary is a suitable solution to increase productivity, conserve energy and develop clean energy.

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