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THE SYNTHESIS AND PRODUCTION CHALLENGES OF QUANTUM DOT BASED SOLAR CELLS

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ABSTRACT

Non-conventional sources of energy are widely being practiced because they are the cleanest and the most abundant source of energy that is available in the earth. Effective utilization of available solar energy to produce the electricity is vital for the increase in the growth of deployment of solar power generation. Owing to the high efficiency and its ease of operation the study of Quantum Dot solar cells has been on an increase ever since the onset of this decade. Extensive research work has been carried out to make these cells more feasible and commercially viable. Some of the areas of this extensive work include Sensitized Solar Cells, Multiple Excitation Effect and Carbon Quantum Dot. The different materials and methods used in quantum dot solar cells are discussed in this article.

Key words: Sensitized Solar Cell, Quantum Dot Solar Cell, Carbon Quantum Dot Solar Cell, Multiple Excitation Generation, Colloidal Quantum Dot Solar Cell

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1. INTRODUCTION

Modern life is mainly depending on the energy consumption from conventional sources. However, there are a limited energy resources that fulfil our energy requirements. There is a vast growth in the field of renewable energy sources such as solar energy, wind energy, biomass etc and it is now replacing the conventional source of energy such as coal, petroleum, natural gas in the upcoming years [1]. One of the serious problem that the world is looking into is the global warming and energy crisis. The Sun showers the earth with enough energy per hour to equal the earth's annual energy consumption per year. So, if some of this energy could be utilised to meet the energy needs that can be useful rather utilising the energy produced from the fossil fuels. As day by day the energy needs have been rising we have to look for some good technologies that that can generate, store and use the energy efficiently. The use of semiconductor materials has been in a great use in the production of clean energy.

Photovoltaic materials are in great use as it can convert sunlight directly into electricity by utilizing the photovoltaic effect.

Solar cells are also called as photovoltaic cells or photoelectric cells that have a potential in the future generation to replace the fossil-based energy sources, but due to its high cost and low efficiency it is not able to replace the non-conventional energy sources. Solar cells are divided into 3 main categories as follows. The first-generation solar cells are made up of crystalline silicon and they are also named as conventional, traditional or wafer-based cells. They are basically made up of single silicon crystal or a block of crystal that is made up of many crystals [2]. The second-generation solar cells consist of thin film solar cell like amorphous silicon, cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS). The performance varies between 10-15% [2]. The third-generation solar cells consist of Dye Sensitized Solar Cell (DSSC) and Quantum Dot Sensitized Solar Cell (QDSSC) and few more solar cells are under research. QDSSC have emerged as one of the most efficient photo electrochemical solar cells. Figure 1 shows the different solar PV tin-film technologies.

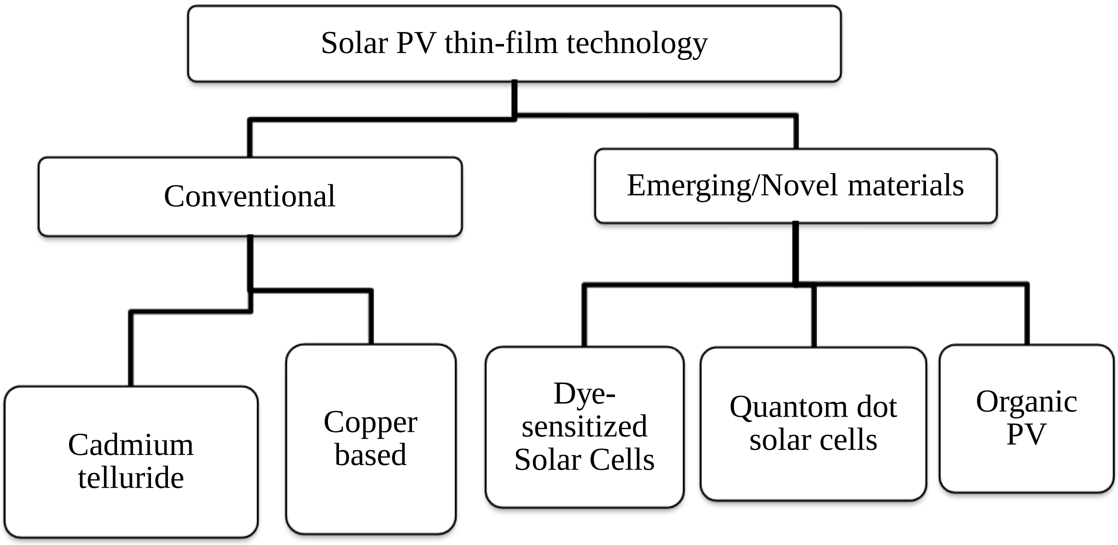

Figure 1 Solar PV thin-film technologies

Graphene on the other hand have some unique properties which can be used in solar cells for various applications. One of the greatest technology in the solar cells that can be of great use is Quantum Dot solar cells. It is a multijunction solar cells based on quantum dots in which multiple p-n junctions made of different materials are used. One of the great use of Quantum dots is that it is used as a sunlight absorbing material. Carbon is a black material and was normally reviewed to have low fluorescence. Carbon quantum dots has been a great area to focus due to its good solubility and good luminescence, for which they are referred as carbon Nano lights [3].

2. SENSITIZED SOLAR CELLS

The involvement of nanoscale considerations on the development of solar cells has had a widescale implication in the overall cost and performance of the solar cells. The conventional solar cells or the first-generation solar cells comprised of very high-grade materials of semiconductors such as Silicon (Si) and Germanium (Ge), whereby offering very little efficiency because of the extraction of the charge carriers at certain points to produce a photocurrent [4]. However, with the usage of Sensitized solar cells (SSC) such the absorbing nanomaterials separation into two different media of photogenerated carriers which involves cost reduction due to the lesser demanding material quality and transport of charge carriers into different materials like the process of decoupling light absorption and charge transport are the fundaments of sensitized cells [5]. These SSC's are of three types:

- Dye-Sensitized Solar Cells: Involve the usage of molecular dyes are used to absorb light.
- Semiconductor Sensitized Solar Cells (SSSC): It involves the usage of semiconductors as the light absorbing material [6].
- Quantum Dot Sensitized Solar Cells (QDSSC): It involves the usage of very small sized semiconductor materials having radius lesser than the Bohr's radius so that the quantum effects of light can be studied [7-9]. This is the main area of interest of this paper.

3. QUANTUM DOT SENSITIZED SOLAR CELLS (QDSSC)

Working principle of QDSSC consists of sensitizing a wide band semiconductor with a semiconductor material of bandgap to near or visible IR region [2]. The maximum used wide bandgap semiconductors are TiO_2 however ZnO [10] and SnO_2 [11-13] have also been reported. The narrow band gap semiconductor Quantum Dot (QD) such as CdS [14-15], CdSe [16-17], PbS [18] and InAs [19] have been used as photosensitizer due to their flexibility in electrical and optical characteristics.[20-23] like:1) Large extinction coefficient, 2) Higher stability towards oxygen and water, 3) depending upon the QD, a tuneable band gap and 4) Multiple Excitation Generation (MEG) using a single photon absorption [24-27]. The theoretical efficiency of QD based on MEG effect is significantly higher compared to the semiconductor solar cells.

3.1. Multiple Excitation Generation Effect

The MEG effect can be used to enhance the overall PCE of the solar cell. It is because of the utilization of the excess energy of the energy of absorbed photon. Hence, more than two electron-hole pairs are generated instead of one pair generated in a conventional solar cell however the band gap required should be twice the bandgap of the QD [28]. It is a phenomenon commonly found in bulk semiconductors however the threshold energy required by electrons are much higher than the QD. Following reasons could be attributed to the integration of MEG effect in QD [29]:

- Due to the formation of discrete electronic layers, the rate of heating and cooling can be slowed.
- The charge carriers' electrons and holes are related. They don't exist independently rather they do it synergistically.
- Due to the multiple electron hole pair generations, the coulomb interaction increases which results in more power generation from the same amount of solar energy as available earlier.

MEG is a process if harnessed properly would lead to a very high solar conversion efficiency [30]. The main reason which could be attributed to this problem is the energy required for the excitation of electrons and pumping of light with high power density [31]. However, there still exists a tremendous potential in improving the solar cells efficiency using MEG effects.

3.2. Sensitization with Inorganic Semiconductors

An inorganic semiconductor can be prepared in several ways which affects the overall performance of the device [32-33]. Some of the techniques employed for the manufacturing of these cells do not require vacuum treatment or high temperature requirements which thereby help in reducing the overall cost of the cell development.

3.2.1. Colloidal Quantum Dots Sensitization

Sensitization with Colloidal Quantum Dots requires the resynthesized CQD growing with a precise control of crystalline material, shape distribution & size followed by attaching it to a nanostructured electrode. Sensitization can be of two types: Assisted and Directed Sensitization. Assisted Sensitization process involves attaching the CQD to the nanostructured photoanode by bifunctional linker molecules [34-35]. The linker molecules generally have a functional group on one side and linker on the other side of the molecule. CQD can also be attached directly to the electrode without the use of any linker group in directed sensitized process. The use of linker molecule is generally useful in the during the CQD analysis because of the long organic molecules tendency to control the QD size and avoiding agglomeration [36]. Although many methods have been proposed in the above two sensitization processes, the following drawbacks have been mainstay in all of these processes which have limited their efficiency and overall application. The process of sensitizer requires the dipping of electrode into the linker molecule which may take several hours to achieve optimum loading value. One technique used to correct this through the electrophoretic technique which involves the two electrodes to be dipped in an QD solution and followed by the application of the electric field. Similar to the process of electrolysis the QD charged particles get attached to one or both the electrodes. CQD deposition will depend upon the applied voltage. However, the performance reported through electrophoretic processes are below compared to the performance for other attaching mode of CQD [5].

3.2.2. Electrode position

One of the most recent and emerging technique of synthesising semiconductor nanostructures and thin films. The process involves the application of electrical potential in the area of conduction of the substrate and counter electrode leading into redox reaction in the liquid. This results in the formation of semiconductor QD on the surface. The main advantage of using this process is that it can easily be used for solar cell applications [37-38] as it offers the possibility of altering the bandgap and lattice constant both through the modulation of parameters such as temperature of the bath, the applied potential and pH. However, this process is limited to electrically conducive materials. A number of semiconductor materials have been formed through the process of electrochemical deposition by varying the various growth parameters, like CdS ,PbS and CdSe. Recent trends have further demonstrated that the number of coating cycles affect the size of the QD [39-40].

3.2.3. Chemical Bath Deposition

It is low cost technique in which the sensitization with inorganic semiconductor takes place through the direct growth on the widegap semiconductor electrode surface through the light absorbing material growth. This method is most convenient for at elevated temperatures to assemble QD on a variety of substrates. The main mechanisms used to achieve this are:(1) bulk precipitation deposition with the bulk diffusion of semiconductor cluster to the coating surface and (2) Coating surface in deposition solution without bulk precipitation by ion by ion deposition [38]. Complex agents are usually utilised to maintain the growth parameters such as chemical bath pH which is directly responsible for controlling the reaction rate and the bulk precipitation of the chemical bath [39]. Following the results of experiments conducted, the nucleation process on surface coating plays a major role in comprehending the formation mechanism of QDs, which is often controlled by the bath temperature and the precursor concentration[40].Earlier researchers have found that recombination resistances have been enhanced by the depositions of QDs by the CBD method densely covering the mesoporous metal oxides[13,41-43].The drawbacks of this method are that for coating and high roughness surface requiring seed layers a number of hours are taken.

3.2.4. Successive Ionic Layer Adsorption and Reaction (SILAR)

An upcoming method, simple, inexpensive and a feasible method for large area deposition of quantum dot such as binary (CdSe, CdS, CuS, CdTe, CuS, Sb_2Se_3 etc) and ternary compounds (CdS_xSe_{1-x}, CuInS, $CuIn_2S_3$ etc) [44-45]. All types of materials can be coated using this method such as insulators, metals and semiconductors as it achieves coating at low temperatures which helps in avoiding the redox reaction of the substrate mostly oxidation and corrosion. The determining parameters essential to control the bandgap and particle size of the QDs are as follows: pH of the precursor solution, concentration of the precursor, nature of complexing agent and absorption, reaction and rinsing time durations etc. The growth mechanism involves the following steps [5].

- Specific absorption of the cationic precursor
- Rinsing of the non-specifically adhered chemicals
- Chemical reaction between the most strongly specific absorbed cations and the least specifically absorbed anions by the substrate immersion in the anion solution
- Rinsing of species that did not react.

This cycle can be repeated a number of times to obtain the required QD size. Although used specifically for metal sulphides, this method has been used to obtain metal tellurides and selenides [46]. Generally, this process has been demonstrated in aqueous medium however there is poor penetration of solution into the porous matrix due to the poor wettability caused by the high surface tension of the liquid. So, solutions with low surface tension are recommended for proper QD coating.

4. CARBON QUANTUM DOT

Carbon quantum dots (CQD) consists of graphene quantum dots as well as carbon quantum dots which comes under a new class of carbon nanomaterials with sizes below 10 nm that has been used in various fields because of its unique properties such as good solubility and strong luminescence, first preference has been given to the carbon based quantum dots and they are also referred as carbon nanolights [47].There has been several methods through which CQD had been prepared in the last few decades which could be classified as Top down and Bottom up approaches, due to its modification during its preparation or post treatment [2].

CQD can be made by pyrolysis of an organic precursor in nanoreactors. The steps which were followed are through the help of capillary force, organic precursor can be absorbed into porous nanoreactors, the pyrolysis of the organic precursor through confinement in the nano reactors into carbonaceous matter and by releasing the asynthesized CQDs which can be done by removing the nanoreactor [3] a shown in Fig.2.

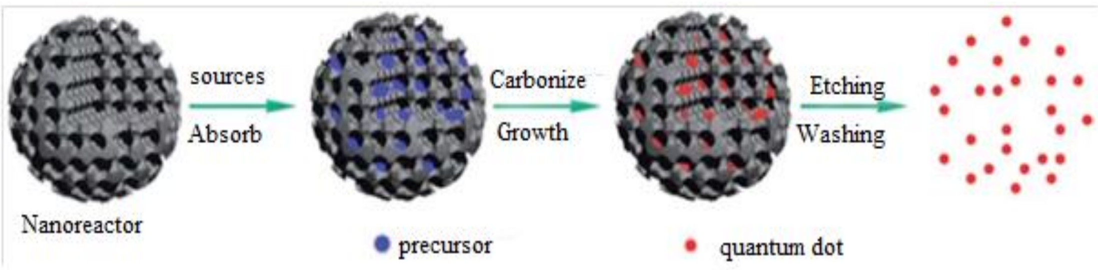

Figure 2 Schematic illustration of the preparation of CQDs via confined pyrolysis of an organic precursor in nanoreactors [3]

The main advantage of CQD is that the oxygen containing groups in CQD is relatively more which helps them easily form covalent bond. One of the methods to improve the photo luminescence of CQDs is by surface passivation through the covalent bonding of amine containing agents which has showed a greater influence in the properties of CQDs. Doping is one of the approach to increase the optical properties of photoluminescent materials. Many doping methods have been implemented such as N, S, and P which has brought a change in the properties of CQDs. As CQD have emerged as a newly fluorescent nanomaterial, they have shown a wide range of applications which includes chemical sensing, biosensing, bioimaging, drug delivery etc. Compared to conventional quantum dots there has been some unique attributes of CQDs such as variable fluorescence emissions etc. has helped them to be very attractive for various technical applications. CQDs are good in excepting and donating the electrons that is why they are efficient in photo luminescence quenching by surface doped metals through distorting the excited state redox process [48]. As the surface of CQDs is very sensitive to contaminants present in the environment, their properties can be easily affected if it is exposed to contaminants [3]. To solve this problem, the surface passivation is a good technique to minimise the effect of surface contamination to their optical properties. Surface passivation is formed by the attachment of polymeric materials on an acid treated CQD surface. To produce high fluorescence intensities CQDs have to undergo this essential step.

5. CONCLUSIONS

The various mechanisms through which the quantum dot solar cell works and its various applications have been highlighted. Multiple Excitation Generation (MEG) using a single photon absorption shows a significantly higher efficiency compared to the semiconductor solar cells. Although extensive research work has been conducted in this field, there still remains a vast scope of improvement in areas of sensitization with inorganic semiconductors especially using the electrodeposition method.

Carbon quantum dots have wide application in the sensing and bioimaging and it should focus purely upon the enhancing the sensitivity, selectivity and robustness of sensing bioimaging platforms. The CQDs have some good fluorescence properties, it is believed that in the future generations it will have a great role to play but one of the disadvantage is that CQDs with high quantum yields still remain few. Many challenges are ahead for the researchers to escalate the quantum yield of CQDs particularly in the arrangement of geometry and structure of the CQDs.

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