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Quantum Dot Solar cells –Properties, Recent Advances and Challenges

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ABSTRACT: Today because of rapid increasing pollution has led industries and researchers to shift towards renewable sources. With this ongoing transition there are many challenges and opportunities that are playing crucial role. This has led to the development of materials having high efficiency. Since the discovery of solar cells there are about 3 generations of solar cell materials, with decreasing cost in each of them. In third generation solar cells there many materials which have high expectation in terms of efficiency. Since few years Quantum dot solar cells have gained attention towards development for high efficiency. With good optoelectronic properties such as tunable bandgap, multiple exciton generation and high extinction coefficient has given rise to the new sector in the solar cell materials. Along with properties, Quantum dot solar also has maximum theoretical efficiency of 66%. For further research it is very important to understand the relation of the properties. This paper gives a brief idea about the quantum dot solar cells, properties, challenges and recent improvements.

KEYWORDS: Quantum dots, multiple exciton generation, hot carriers.

I. INTRODUCTION

Today with the depletion of the fossil fuels there has been a huge transition towards renewable energy sector. Every country is moving towards the renewable energy sector. Since past few years European and Asian countries have installed many solar power projects. Many future predictions are done and justified that oil can be replaced by renewable energy(1).The countries in Asia-Pacific region with the increase in demand of the electricity in addition with the renewable energy policy, Asia-Pacific region will see a rapid development in the renewable energy sector. Along with Asia-Pacific countries like Canada, USA will also have development in the renewable sector.

Solar panel is one of the main components in the whole solar power project. This device is solely responsible to convert the sun radiation into electricity. These panels consist of the solar cells and depending on the material there are various different types of panels with the ranging efficiencies.

Solar cells are classified into three generations. First generation consists of Mono and poly-crystalline solar cells. They have efficiency ranging from 15% to 25% and manufacturing costs are high. Mono- crystalline solar cells are manufactured by the process Czochralski process. In this process Silicon crystals are sliced from the big ingots. Due to which there cost is high. Poly-crystalline solar cells modules are collection of a number of silicon crystals by melting they are combined together in a single cell. Polycrystalline solar cells are widely accepted and in 2008 48% of production was reported. Second generation consists of thin film solar cells these are less expensive solar cells but the efficiency is lower as compared to first generation solar cells.Thin film solar cells are deposited on the flexible substrates such as glass, plastic and metals. Thin film solar cells have efficiency ranging from 4-15%. Third generation solar cells are classified into different types such as Nano crystal based solar cells, Polymer based solar cells, Dye synthesized based solar cells. Third generation solar cells do not rely on the p-n junction design. Variety of new materials is used like nanomaterials, silicon wires, solar inks, organic dyes. These cells have enhanced electrical performances as compared to second generation and also low production costs. Third generation solar cells are currently undergoing research.(2)

Among these third generation solar cells quantum dot solar cells have gained interest due to their optical and electronics properties. Quantum dot solar cells are also called as Nano-crystal based solar cells. Quantum dot solar cells are used to replace the semiconductor material in a bulk state such as Si, CdTe. These solar cells because of their remarkable and unique properties have promised to lower down the production cost and simultaneously increase efficiency(3)

II. QUANTUM DOT PROPERTIES

Quantum dots first came into existence when they were first synthesized by Alex Ekimov in 1981 and in colloidal suspension by Louis Brus in 1983. Due to their remarkable properties of quantum confinement many attempts are made to increase efficiency. Quantum dots are the semiconductors with the diameter ranging from 1-100nm. Nanostructures are classified into different types such as 1-Dimensional, 2-Dimensional, 3-Dimensional and 0-Dimensional. In 1-Dimensional only one dimension is stronger than the other two. Incase of 2-Dimensional structure only two dimensions are larger than third, 3-Dimensional are matrix formed by aggregation of nanoparticles. 0-Dimensional nanostructures have all dimensions nanometers wide(4).

One of the properties that differentiate quantum dots from other is dependency of their optoelectronic properties on the size of Nano crystals.Bulk materials such as silicon do not exhibit photoluminescence but when it comes to quantum dot it can exhibit. Quantum dot solar cells have tunable bandgap. The relation between bandgap and size of quantum dot is inversely proportional. Thus bandgap can be tune to match a photon energy range (5).

Another important property of the quantum dot solar cells is effective use of thermalization process. In bulk materials thermalization is one of the limiting factors for the solar efficiency. Thermalization is the absorption of the high photons i,e the energy of photons is twice the bandgap of the material. Schockley Queisser limit for the single layer solar cell is about 31%. This is the theoretical efficiency that a single layer solar cell can achieve. It is affected by thermalization process of about 33%.

In a semiconductor the photon with energy below band gap is not absorbed and they just pass through the material. When the energy of photons is equal to band gap then it is absorbed by the semiconductor and thus create a exciton i,e electron-hole pair. This photo generated carrier is separated and charge carriers will be conducted towards external contacts. Now when the energy of the photons is twice the band gap, they are absorbed by the semiconductor and hot carriers are generated which has high energy and eventually return to a stable sate by relaxation process. Thus there is not an effective use of hot carriers and we get low efficiency. So major part of energy in semiconductor is lost as heat. So inorder to use this energy there are 2 ways 1. Intermediate band solar cells 2. Hot carriers.

1 Intermediate solar cell

According to Schockley Queisser limit single layer solar cell is limited by the efficiency of 31%. Major part of the energy is lost as heat through electron phonon scattering and subsequent phonon emission, as the carriers relax in their respective band edges. As show in Fig 1.In order to utilize this waste heat the main approach is to use cascaded or combination of multiple p-n junctions with varying band gaps and better matched to the solar spectrum. Because of this method high energy photons will be absorbed by higher band gap semiconductors and lower energy photons by lower band gap semiconductors. This reduces the overall heat loss due to carrier relaxation via phonon emission.(6)

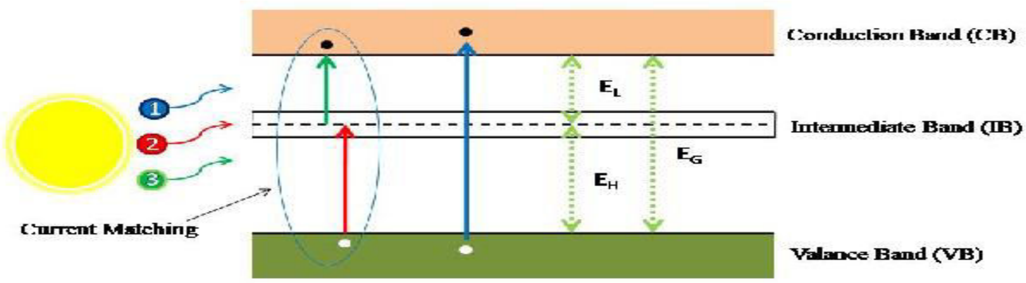

Figure 1 Architecture of Intermediate band gap solar cell

2. Hot carriers

Hot carriers play a very important role. Whenever a photon with high energy (twice the energy than band gap) is incident then the thermalization occurs. In order to use this high energy effectively there are two techniques, before the device cools down remove the hot carrier from it thereby obtaining high energy and thus higher voltage output is obtained. For making this possible the rate of hot carrier separation, transport and connection at contacts must be greater than the rate of cooling hot electrons. Refer to Fig – 2a

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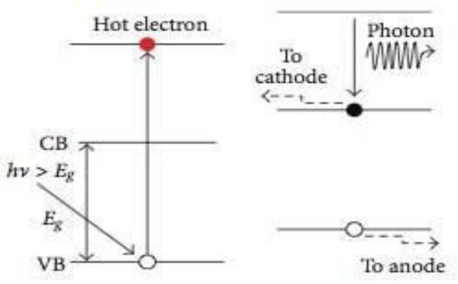

Figure 2a Photon with energy higher than band gap

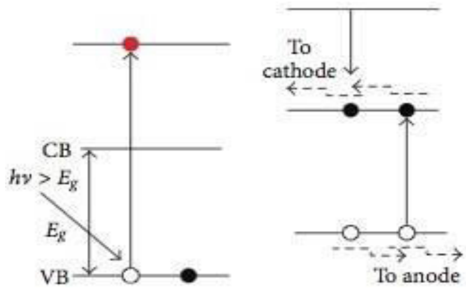

Figure 2b Mechanism of Impact ionization

The second approach to utilize the hot carriers effectively is by photocurrent. Refer to Fig – 2b. This method requires the energetic hot carriers. These hot carriers are able to produce 2 electron hole pairs thus increasing the efficiency of the solar cells. This method is also called impact ionization. Impact ionization process occurs only when rate of relaxation is less than carrier cooling(7).

III. ADVANCES IN QUANTUM DOT SOLAR CELLS

Bowen Fu(8)worked on improving the efficiency of the $CuInS_2$ Quantum dot solar cells by improving the charge recombination. Author fabricated $CuInS_2$ Quantum dot solar cell by using a spin coating assisted SILAR method and further used as photo electrodes for solid state QDSSCs. Refer to the Fig 3. It is proved that by increasing the number of cycles materials can enhance the absorption ability. TiO_2 compact layer was fabricated with the thickness of 70nm by spin coating on the FTO glass at an rpm of 400 for 30 seconds. Further, dilution and annealing process were employed.This annealing plays a very important role. It enhances the contact between $CuInS_2$ quantum dot and TiO_2 by reducing the probability of internal photogenerated carrier recombination. Following results were obtained refer to Table 1

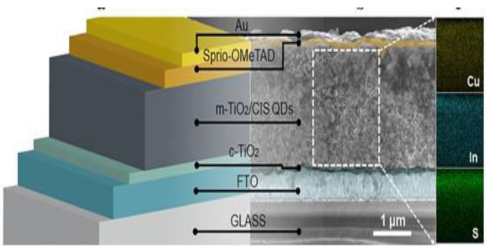

Figure 3 SEM image of the solar cell after annealing at 400deg cell

Table 1 Photovoltaic parameters obtained from the J-V curves of QDSSCs using TiO2/CIS films annealed at different temperatures as photo electrodes

Temperatures	V_{OC} (V)	J_{SC} (mA cm^{-2})	FF	PCE(%)
200 °C	0.50	5.63	0.37	1.04
300 °C	0.53	7.76	0.41	1.68
400 °C	0.68	11.33	0.41	3.13
500 °C	0.68	8.58	0.42	2.44

As shown in the table most suitable annealing temperature for TiO2 / $CuInS_2$is400 °Cwhich gives a highest efficiency of 3.13% and longest electron lifetime of about 117ms.

Xiaoliang Zhang(9) Studied on colloidal quantum dot solar cells and improved efficiency by electron extraction by using MgZnONano crystals for flexible quantum dot solar cells. As shown in the Fig 4a,b device structure was colloidal quantum dot solar cell with MgZnO as an electron transport layer. Simulations were performed under AM 1.5G 100 mW/cm^2 illumination. The simulated result from optoelectronic model concluded that CBM of the Electron layer significantly affects the photovoltaic performance.

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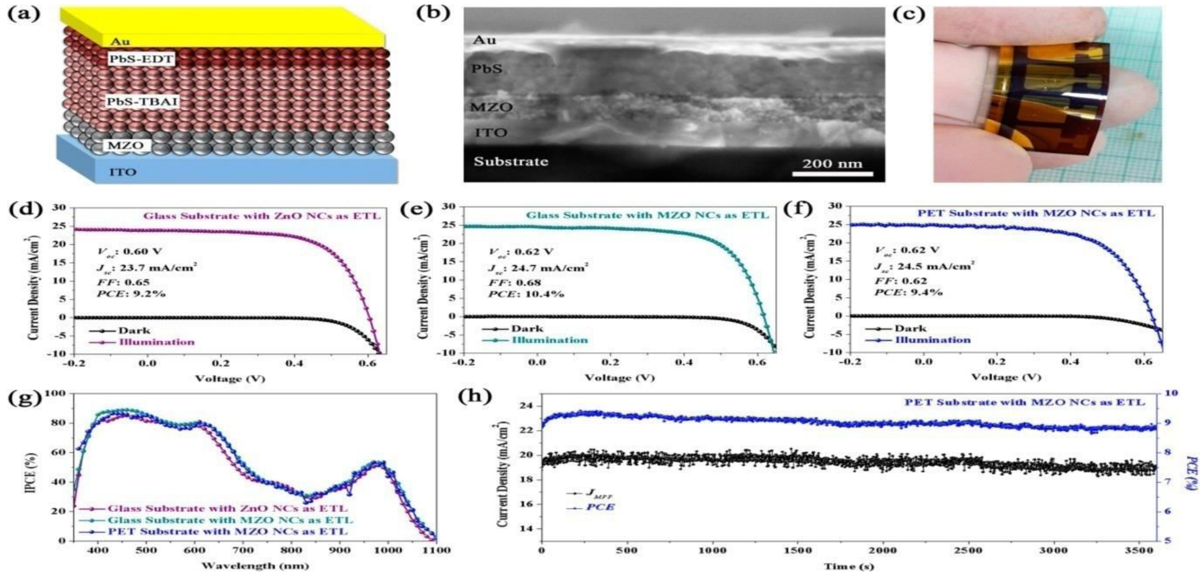

Figure 4. Solar cell photovoltaic performance. (a) Schematic device architecture of CQD solar cell. (b) Cross-sectional SEM image of CQD solar cell with MZO-NCs as an ETL. (c) A photograph of flexible CQD solar cell. J−V curves of the solar cell fabricated on the glass substrate with (d) ZnO-NCs and (e) MZO-NCs as ETL, respectively. (f) J−V curves of the flexible CQD solar cell with MZO-NCs as ETL. J−V curveswere measured under AM1.5G 100 mW/cm2 illumination and dark conditions. (e) IPCE spectra of above solar cells. (g) Steady-stateefficiency and photocurrent density of the flexible solar cell with MZO-NCs as an ETL at the MPP under continuous AM1.5G 100 mW/cm2 illumination.

Refer to the Graphs 4. J –V graph is plotted. Because of efficient charge extraction enhanced built-in potential in the colloidal quantum solar cell with MgZnONano crystals as an electron transport layer, photon conversion efficiency as high as 10.4% and 9.4% is achieved. Other than this, architecture also offers better stability under both continuous illuminations and ambient storing conditions.

Mahmoud Samadpour(10)Studied various semiconductor sensitizers such as CdS, CdSe, CdS/CdSe, and PbS/CdS and found out that by using CdS pre-deposition will enhance efficiency and increase electron life time. For investigating the electron life time applied bias voltage decay method is used. For conducting this experiment photo anodes and cathode were prepared. Photo anode electrodes were prepared by the deposition of two TiO_2 layers on the fluorine doped tin oxide glass substrates. Fig 5 shows the scanning electron microscope micrograph of the layers which are made TiO_2 paste.

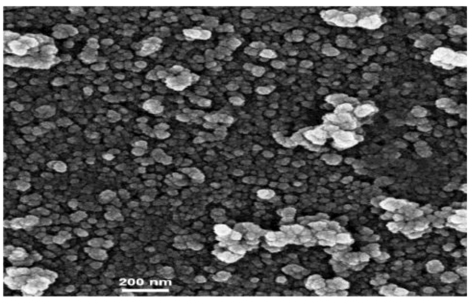

Figure 5 SEM micrograph from the layers which are made by TiO2 paste.

Table 2 Photovoltaic parameters of the QDSCs: photocurrent jsc, open circuit voltageVoc, fill factor FF, and efficiency E, as a function of the sensitizer type.

Sensitizer Type	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF	E (%)
CdS	493	4.34	0.53	1.13
PbS/CdS	459	8.55	0.47	1.84
CdSe	556	10.86	0.47	2.84
CdS/CdSe	556	10.52	0.62	3.63

Table 2 shows the current voltage properties which are sensitized by CdS, CdSe, PbS/CdS, and CdS/CdSe Quantum Dots. It also shows the results which indicate that by CdS pre deposition efficiency is improved by 2.43% which is 25% more than CdSe sensitized cells.

Gyea Young Kwak(11)Studied on the improvement of the efficiency of Si quantum dot solar cells with boron implantation. Author addressed the issue of activation of fabrication of Si and B as it's not effective because high concentration Boron is required for effective activation. So inorder to solve this issue experiments were conducted to effectively implant boron by using method called ion implantation. For architecture Ref to the Fig – 6

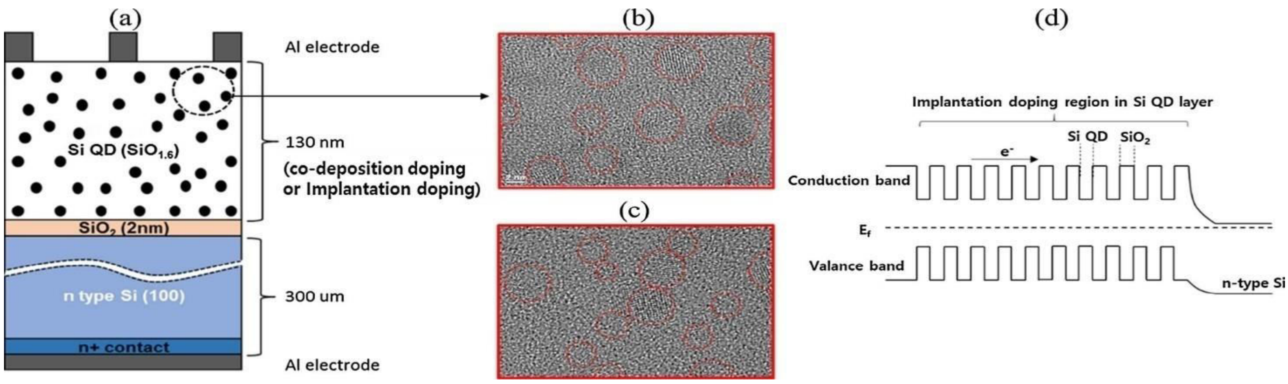

Fig. 6. Schematic diagram of silicon quantum dot solar cells (a) and TEM images of Si quantum dot layers formed by the co-deposition method (b) and by the B implantation method (c) and schematic energy band diagram of B doped Si QD (d).

Table 3
J-V characteristics of CD-QD SCs and BI-QD SCs (*all data are averaged from four samples in each case).

Type	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	Eff (%)
BI-QD SC	529.64 ± 0.89	34.36 ± 0.53	76.55 ± 1.14	13.92 ± 0.05
CD-QD SC	523.03 ± 1.08	33.17 ± 0.42	75.93 ± 1.25	13.17 ± 0.13

The activation of the B atoms were investigated bycomparing two Si QD solar cells using a B-doped Si QD layer created bya co-deposition (CD-QD SCs) process and a similar layer created by Bimplantation (BI-QD SC) at the similar doping level of about9.4 × 1020 atoms/cm^3. As shown in Table-3 following results were obtained, by using this method efficiency is increased from 13.17% to 13.92%. Open circuit voltage is also increased from 523.03 mV to 529.64 mV.

IV. Challenges

1. Less efficiency.(12)
2. There has been more use of toxic materials.(12)
3. In order to increase efficiency there is a use of heavy metal elements.(12)
4. The process of making Quantum dot is not eco-friendly.(12)

V. CONCLUSION

Quantum dot's solar cell gets differentiated due its remarkable properties compared to other solar cells. Today highest conversion efficiency of quantum dot achieved is 16.6%. Despite having unique properties quantum dots have been stumbled in terms of efficiency. There are many challenges as discussed earlier to which further research is needed in order to solve the problems. Quantum dot's theoretical efficiency is quite bigger as compared to other solar cells this is one of the fascinating point of the quantum dot solar cell. As Quantum dot solar cells belongs to the third generation family there are many research opportunities. In the future quantum dot solar cells can be a main contender to compete in a solar photovoltaic market by reducing cost and simultaneously increasing efficiency.

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