Advanced Research in Electrical and Electronic Engineering
Print ISSN: 2349-5804; Online ISSN: 2349-5812 Volume 2, Number 10 April-June (2015) pp. 76-80

http://www.krishisanskriti.org/areee.html

A Concise Review of Quantum Dot Solar Cell: Its Potential and Challenges

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Abstract—*In the field of photovoltaics, high efficiency and low cost are simultaneous goals that need to be achieved in order to meet the world's ever growing energy demands. In contrast with bulk materials such as silicon, copper indium gallium selenide (CIGS) or cadmium telluride, quantum dots have emerged as highly promising materials to be used as sensitizer for trapping solar energy and converting it into electricity. The prospective performance of solar cells has led to wide spread research in this field. Size dependent band gap of quantum dots allow harvesting of full spectrum of solar energy. They offer increase in the maximum attainable thermodynamic conversion efficiency of solar cells. Some advancements in the field of dye sensitized solar cells (DSSC), quantum dot sensitized solar cells (QDSSC) and bulk heterojunction (BHJ) solar cells have been discussed in this review. Different methods of designing of photoanode, effect of various electrolytes and counter electrodes have been discussed. Quantum dots can be combined with other nanostructures, whose properties can be simultaneously exploited for enhancing the solar cell efficiency. Various mechanisms to improve the performance of solar cells such as multiple exciton generation, hot electron transfer, coupling of dye molecules with quantum dots, tandem layer solar cell, nanowire quantum dot composites and quantum dot-carbon nanotube hybrid assemblies have been found.*

1. INTRODUCTION

Extensive usageoffossil fuels hasalsoledtolarge CO_2 emissions and increaseintheglobalmean temperature [1]. Fossil fuel resources need tobe replacedwithrenewable resourcesto meet the world'sfuture energyrequirements. Photovoltaic solarcellswillplayavitalroleinchecking the energycrisis[2].Solar cells have evolvedoverthree generations.Maximumefficiencyof25%hasbeenshownby firstgenerationpassivatedemitterrearlocallydiffused(PERL) Sibasedsolarcell[3].Thinfilmstructures whichconstituted the secondgenerationwere cheaperto produceas they eliminatedthe cost of siliconwafer. Polycrystalline $CuInGaSe_2$ cellgave maximum recorded efficiencyof19.9% [4]. Third generation solar cellshave evolved from nanostructure architectures[5]. Nanostructureshavemany advantages whichhelp themachievehigherefficiencyand low costper watt. Theyarei) increasednumberofenergy levelsii)generationofmultiplecarrierswiththehelpofsingle highenergyincident photon [65] and iii) reductionof thermalization lossesbycapturing carriersbefore theyrelax. Thethreemostdominantlyresearchedarchitecturesarea)dye sensitizedsolarcell (DSSC)b) bulk heterojunction (BHJ) solar cellc) quantumdot solar cell. Most basicoperation involved inDSSC istransfer ofphotoexcitedelectronfrom dyetowidebandgapsemiconductor,typicallyTiO2whereas themaineventincaseofBHJsolarcelliselectron injection fromconjugated polymertoelectronaccepting fullerene.In 2012report,zinc-porphyrindyebased solarcell usingCo (II/III)tris(bipiridyl)as redoxelectrolyteshowedrecord efficiency of 12%[7]. Bulk heterojunction solar cell using thieno[3,4-c]pyrrole-4,6-dione andDithieno[3,2-b:2',3'-d]silolecopolymer and$PC_{71}BM$ showed remarkable efficiency of 7.3%[8]. Impressive sensitivity for capturing light andtunablebandgapmakesemiconductornanocystal quantumdotssuitable candidates forbeingusedassensitizer insolarcells[9].

2. QUANTUM DOT SENSITIZED SOLAR CELL

Quantumdotsolarcellsareconsideredaspre-eminentenergydevices forreasonsbeinga) ability togenerate multiple electron-hole pairs b)simple fabricationtechniques andc)low fabrication cost. A QDSSC consists of a QD sensitizedphotoanode,counterelectrodeand electrolyte. Mesoscopicwidebandgap semiconductoroxidelayer, particularlyTiO_2,makesthephotoanode.TheQD sensitizeris adsorbed on theTiO_2[10]. On illumination, electron gets excitedacrosstheQDband gapand isthen finallyinjected intothe TiO_2 layerleadingtooxidation of theQDs.This injected electron can moveintotheexternalcircuitthrough theporousTiO_2.

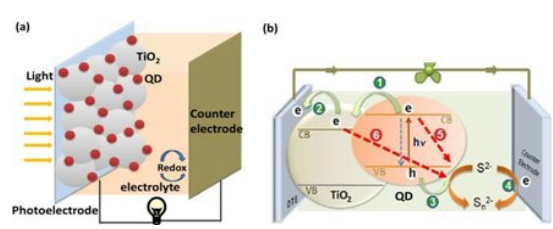

Fig. 1: (a) Schematicview ofstructure of QDSSC (b) SchematicillustrationofchargetransferprocessofQDSSC[9].

3. DEPOSITIONOFQDSFILMSONSEMICONDUCTINGELECTRODESFORQDSSC

Most important requirement for designing of QDSSC is formationofassemblyofQDsonTiO2film[10].TheTiO2film islayeredon OTE(opticallytransparentelectrode).TheseQD layered photoanodes become sensitive to solar light absorptionandcanbeusedfor trappingthesolarenergy.Drop casting orspincoating aremostcommonly usedmethods to designphotoactiveanode.Chemicalbath deposition(CBD) involves dippingof electrode into bathsolution containing both cationicandanionicreactantswhereas SILARinvolves dipping of electrode sequentially into separate prepare dryingoftheelectrodeatsuitabletemperature. This whole process is termed as SILAR cycle.The numberof SILAR cyclesdetermines the thicknessofthe film deposited. DC electricfieldisappliedtoelectrodesdippedin QDsolutionfor electrophoreticdeposition[12]. Temperature,solution composition andduration ofdeposition definethequalityof filmdeposited. Eachmethodhas itsownadvantageand disadvantagedependinguponthetargetedinvestigation.Close contactisprovidedbetween quantum dotsandwidebandgap semiconductor TiO2 film by chemicalbath deposition and surface ionic layeradsorption andreaction processes. Therefore,fordesigning of photoanode forthe purposeof solarcells, CBD and SILARprovetobeexcellentchoices. Bothofthesemethods resultinnon-crystalline products.For crystallization oftheproduct itmayneedtobesubjectedto annealing. For impressivesize selection of quantum dots withintheQDfilm,electrophoretic depositioncomesoutasa usefulmethod.ThesemethodstodepositQDfilmon theTiO2 anodehavebeenillustratedbrieflyinfigure2.

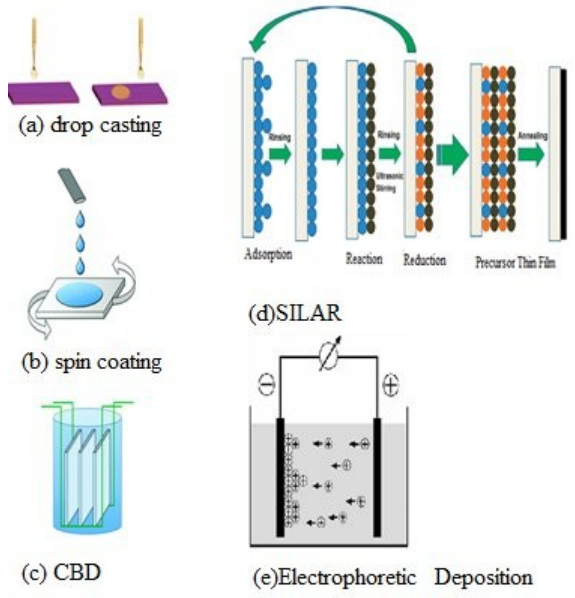

Fig. 2:Schematic illustration ofdepositing QDsuspension onsemiconducting electrodesurface

Table 1: EfficienciesofdifferentQDSSCs.

Substrate	Photoactive material	Counter electrode	Electrolyte	Efficiency(η%)	Reference
FTO/TiO2	CH3NH3PbI3	Au	Li-TFSI/acetonitrile/TBP	9.0	13
TiO2	CH3NH3PbI3	Pt	LiI/TBP/urea in ethylacetate	4.73	14
TiO2	CdSe	Cu2S	PyrolidiniumIL in acetonitrile	1.86	15
FTO	CdSe/CdS/ZnO nanowire	MSU-F-C	Polysulfide	3.6	15
FTO/TiO2	CdS/CdSe	CoS2	Polysulfide	4.16	16
TiO2/CuInS2	CdS/ZnS	PbSfilm	Polysulfide	4.7	17
FTO	ZnO/ZnSe/CdSe	Cu2ZnSnS4	Polysulfide	3.73	18
FTO	ZnO/ZnSe/CdSe	Pt	Polysulfide	2.72	18
TiO2/CuInS2	CdS/ZnS	CuS	Polysulfide	4.2	19
TiO2	CdSe	Pt	Polysulfide	0.75	20
TiO2	CdSe	PbSfilm	Polysulfide	3.01	20
TiO2	CdS/CdSe	Cu2S	Polysulfide	3.27	21
FTO/TiO2	CdSe	Pt	Polysulfide	2.55	22
FTO/TiO2	CdSe	Cu2ZnSnS(Se4)	Polysulfide	4.35	22
TiCl4 treatedTiO2	CdS	Pt	Polysulfide	0.65	23
Nc-TiO2/FTO	CdSe/CdS	Pt/FTO	Polysulfide	0.51	24
Nc-TiO2/FTO	ZnS/CdSe/ZnS- CdS	CuS/FTO	Polysulfide	2.7	24
TiO2	CdS	Cu1.8S/CuS prepared by hydrothermal method	Polysulfide	1.66	24
F-TiO2	CdS/CdSe	PorousCu2S	Polysulfide	0.72	25
P20-TiO2	CdS/CdSe	PorousCu2S	Polysulfide	2.57	25
TiO2	CdS/ZnS	Pt	Polysulfide	0.82	26
TiO2	CdS/ZnS	CuS	Polysulfide	1.72	26
TiO2	CdS/ZnS	Cu2S nanopallet sonPt	Polysulfide	2.27	26

4. TECHNIQUES TO ENHANCE SOLAR CELL PERFORMANCE

Many approaches have been developed in recent advances which help in improving the power conversion efficiency of quantum dot based solar cell. Quantum confinement effect in quantum dots allows the extra energy of single incident photon to be easily converted into multiple carrier or exciton (electron hole pair) generation. Excitation process in quantum dots is faster than the cooling or relaxation of charge carriers resulting in effective charge separation. This fast and efficient drifting of carriers from working electrode to the counter electrode accounts for improved efficiency [27]. Schaller et al. in 2004 observed the phenomenon of multiple exciton generation for the first time [29]. In PbSeQDs MEG enhance the performance two times more thanPbSe bulk [28]. Thermalization losses in solar cells can be reduced by utilizing hot carriers thereby increasing overall efficiency [30].ZnO nanowire array solar cells coupled with CdS QDs booststhe absorption capacity. Yangjo et al. carried out acomparative study of bare ZnO nanowire/ TiO2 and ZnOnanowire/CdS QDs on TiO2 substrates as photoanode in solarcell. Improvement in efficiency was recorded from 3.53% to4.15% respectively [31]. P-i-n doped InP nanowires overcamethe dependency on length, diameter and coverage ofnanowires by showing remarkable efficiency of 13.8% [32].Coupling of QDs with dye molecules increases efficiency byintroducing efficient charge separation [33]. Shalom et al. showed increment in efficiency from 0.57% to 1.51% by sensitizing CdS QDs with dye N719 using I3-/I- redox couple as the electrolyte and Pt as counter electrode [34]. Absorption spectrum of solar cells can be increased by using multilayered or tandem solar cells. TiO2/CdS/CdSe tandem structure shows high efficiency of 4.4% while using composite of RGO and Cu2S as counter electrode [35]. Use of multilayer QD thick film offers the advantages of increase in the number of absorbed photons and reduction in diffusion length, thus lowering the recombination process. Shalom et al. showed solar cell with multilayer QD film of thickness 60 nm gave efficiency as high as 3.86% [36].Introducing carbon nanotubes in QD film result in considerable improvement in conductivity and charge separation. It allows unhindered hopping of electrons through the QD film without or low recombination of charge carriers [37].Doping of transient metals such as manganese creates an intermediate band between conduction and valence band thus allowing easier jumping of electrons. Punoose et al. showed TiO2/PbS/ Mn doped CdS quantum dot solar cell gave efficiency of 3.55% [38]. In bulk heterojunction architecture fullerene can be replaced by quantum dots to enhance the performance values [39]. In depleted heterojunction solar cell, maximum efficiency is recorded in depleted region for short circuit conditions [40]. Maraghechi et al. adopted a new technique of using donor-supply electrode. They coupled highly doped FTO with moderately doped, very thin TiO2 film. This resulted in increased depletion layer width into the TiO2 film. Performance improved by 10% in comparison to highly doped TiO2 film [41]. Size dependent performance of CuInS2 QDs shows efficiency of 2.14% and 2.51% for 3.9nm and 4.3nm respectively. Although efficiency recorded were lower for large sized QDs (5.3nm) due to reduced charge separation [42].

5. CONCLUSION

Quantum dots with their size varying bandgap offer the possibility of covering the entire solar spectrum. Quantum dot solar cells have found tremendous improvement in their efficiency in the last few years. Their composites with other materials such as carbon nanotubes, polymers, nanowires promise further improvement in the overall performance of solar cells. Transformative technology needs to be adopted in near future. Use of quantum dots in technologies such as solar paints and reel to reel printing suggest that quantum dots will stay long in the field of photovoltaics.

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