SYNTHESIS OF CADMIUM SELENIDE AND CADMIUM TELLURIDE CO-SENSITISED QUANTUM DOTS VIA THE SILAR METHOD

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To my beloved family

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ABSTRACT

Third generation solar cells such as Quantum Dot Sensitized Solar Cell (QDSSC) have the potential to overcome the Shockley-Queisser limit and achieve higher efficiency than the first and second generations. However, there are still challenges in achieving the theoretical efficiency for QDSSC, which is still an open space for further research. Among the various materials used for QDSSC, CdSe quantum dots (QDs) are widely used as it can be tuned to absorb a wide range of absorption wavelength. However, there are still limitation in the absorption wavelength up to near infra-red region that can be further improved with method such as co-sensitizing with another material such as CdTe. In this study, successive ionic layer adsorption and reaction (SILAR) method was used to co-sensitized CdSe/CdTe QDs with onto titanium dioxide (TiO_2) nanorods array grown on Fluorine doped Tin Oxide (FTO) coated glass. Three variation of SILAR method were used to synthesize CdSe QDs on TiO_2 nanorods with 1-8 number of cycles. This first step was used to understand the effect of SILAR method on CdSe QDs and to select the best SILAR method to proceed with the synthesis of CdTe QDs. The CdSe QDs with best absorption result were then used to be co-sensitized with CdTe QDs. Among the three variation of SILAR methods, the inverse SILAR method shown the highest consistency in absorption intensity using the UV-Vis spectroscopy. The increase in the number of SILAR cycles resulted in the increase in the amount of QDs and the aggregation was clearly observed around seven cycles onwards as observed by field emission scanning electron microscopy (FE-SEM) and transmission electron microscopy (TEM). It was found that five cycles were the optimum cycle to avoid the aggregation and yet achieve the highest absorption intensity. Hence, CdSe(5) sample were chosen to be further co-sensitized with CdTe QDs. The co-sensitized sample, CdSe(5)CdTe(5), shows a higher absorption intensity and wider absorption range as compared to the CdSe(5) sample. Furthermore, the CdSe(5)CdTe(5) sample shows the highest efficiency of 0.018 % measured using the electrochemical impedance spectroscopy (EIS) and solar simulator. This conclude that the co-sensitization was able to improve in harvesting ability.

ABSTRAK

Sel solar generasi ketiga seperti Quantum Dot Sensitized Solar Cell (QDSSC) berpotensi untuk mengatasi had Shockley-Queisser dan mencapai kecekapan lebih tinggi daripada generasi pertama dan kedua. Walau bagaimanapun, terdapat juga cabaran dalam mencapai kecekapan teori untuk QDSSC, yang masih merupakan ruang terbuka untuk penyelidikan lanjut. Antara pelbagai bahan yang digunakan untuk QDSSC, titik kuantum CdSe (QDs) digunakan secara meluas bahawa ia boleh ditala untuk menyerap julat panjang gelombang penyerapan yang luas. Walau bagaimanapun, terdapat juga had panjang gelombang penyerapan berhampiran kawasan inframerah yang boleh ditambahbaik lagi dengan menggunakan kaedah seperti pemekaan bersama dengan bahan lain seperti CdTe. Dalam kajian ini, kaedah SILAR telah digunakan untuk mensintesis titik-titik kuantum CdSe/CdTe terpeka bersama dengan susunan nanorod TiO_2 yang ditanam pada kaca bersalut Tin Oksida berdop Flourine. Tiga kaedah variasi SILAR digunakan untuk mensintesis CdSe QDs pada nanorod TiO_2 dengan 1-8 bilangan kitaran. Langkah pertama ini digunakan untuk memahami kesan kaedah SILAR pada CdSe QDs dan memilih kaedah SILAR terbaik bagi meneruskan sintesis CdTe QDs. Hasil penyerapan CdSe QDs terbaik akan digunakan untuk dipekakan bersama dengan CdTe QDs. Antara tiga kaedah variasi SILAR, kaedah SILAR songsang menunjukkan ketekalan tertinggi dalam keamatan penyerapan yang dicerap menggunakan spektroskopi UV-Vis. Peningkatan bilangan kitaran SILAR mengakibatkan peningkatan dalam jumlah QDs dan pengagregatan telah diperhatikan kira-kira tujuh kitaran dan seterusnya seperti yang diperhatikan oleh mikroskop elektron pengimbasan pelepasan medan (FE-SEM) dan mikroskop elektron penghantaran (TEM). Didapati lima kitaran optimum untuk mengelakkan pengagregatan tetapi mencapai keamatan penyerapan yang paling tinggi. Oleh itu, sampel CdSe(5) telah dipilih untuk lebih peka dengan CdTe QDs. Sampel kepekaan bersama, CdSe(5)CdTe(5), menunjukkan keamatan penyerapan yang lebih tinggi dan julat penyerapan yang lebih luas berbanding dengan sampel CdSe(5). Tambahan pula, sampel CdSe(5)CdTe(5) menunjukkan kecekapan tertinggi iaitu 0.018 % yang diukur menggunakan spektroskopi impedans elektrokimia (EIS) dan simulator suria. Ini menyimpulkan bahawa pemekaan bersama dapat meningkatkan keupayaan penuaian.

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LIST OF SYMBOLS AND ABBREVIATIONS

m	-	Micro
M	-	Molar
n	-	Nano
Ɵ	-	Angle
s	-	Second
µ	-	Micron
$CdCl_2$	-	Cadmium Chloride
CdSe	-	Cadmium Selenide
CdTe	-	Cadmium Telluride
DSSC	-	Dye-Sensitized Solar Cells
EDS	-	Energy dispersive X-ray spectroscopy (EDS)
EIS	-	Electrochemical Impedance Spectroscopy
FESEM	-	Field Emission Scanning Electron Microscopy
QDSSC	-	Quantum Dot Sensitized Solar Cells
FTO	-	Fluorine doped Tin Oxide
H_2O	-	Water
H_6N_2O	-	Hydrazine Hydrate
HCl	-	Hydrochloric Acid
J-V	-	Density-Voltage
KCl	-	Potassium Chloride
$Na_2S·9H_2O$	-	Sodium Sulfide
Na_2SeSO_3	-	Sodium Seleniosulfide
NaOH	-	Sodium Hydroxide
SILAR	-	Successive Ionic Layer Adsorption and Reaction
TiO_2	-	Titanium Dioxide
XRD	-	X-Ray Diffraction
ZnO	-	Zinc Oxide

LIST OF PUBLICATIONS

1. Soo, J.Y., Ameruddin, A. S. B., & Ahmad, M. K. B. (2022). Co-Sensitising Cadmium Selenide And Cadmium Telluride Quantum Dots On Titanium Dioxide Nanorods Via The Silar Method. Chemical Physics Letters, 140170.

CHAPTER 1

INTRODUCTION

1.1 Research background

The urge to use clean renewable energy is on the rise due to the negative impact of carbon-emitting energy resources such as global warming and climate change. Gielen *et al*., (2019) stated that energy-related to carbon dioxide (CO_2) contributes to about two-third of all greenhouse gases (GSG). Among the candidate for producing large amount of clean energy, solar energy is one of the candidates that standout. Hence, research on the efficiency and technology of solar energy has been of interest in the last few decades (Morton, 2006; Timilsina *et al*., 2012). The 1st generation of solar cells was made by conventional silicon wafer such as mono- and poly- crystalline silicon solar cell (Anurag *et al*., 2020). The 2nd generation solar cell was developed to overcome the limitation of the 1st generation solar cell such as high production cost (Tvrdy *et al*., 2011) and the bulkiness of the solar cells. The 2nd generation of solar cells was also called as thin film solar cells (Ali *et al*., 2016). Some of the examples are CdTe solar cells (D. Wang et al., 2021), copper indium selenide (CIS) (Palm et al., 2004), and Copper indium gallium selenide (CIGS) solar cells (Bouabdelli et al., 2020). Even though they take up less space, their efficiency was less than the 1st generation solar cell (Kibria *et al*., 2014). In 1961, Shockley and Queisser developed a theory stated that the limiting efficiency of a single junction solar cell (Xu *et al*., 2015), limits the 1st generation solar cells to produce maximum efficiency around 32% due to its single P-N junction (Ehrler *et al*., 2020). Therefore, there is a need to find other methods to increase the efficiency of the solar panels (Rao & Friend, 2017). This has led to the rise of the multijunction solar cell. Multijunction solar cells utilize materials with different bandgap in tandem so that more photon energy will be able to be

absorbed by the solar cell (Tvrdy *et al*., 2011). Multijunction solar cell can produce conversion efficiency higher than the limit of Shockley-Queisser however such device is severely limited. Hence, to overcome the efficiency limitation of single bandgap and the limitation to produce multiple junction solar cells, third generation solar cells was developed. The 3rd generation solar cells such as dye-sensitized solar cells (DSSC) have short-term stability (Ranabhat et al., 2016) and mass transport limitation result cause low power conversion efficiency (PCE) (Bandara & Weerasinghe, 2005). On the other hand, QDSSC have the potential to reach a PCE of 44% (Z. Du, Artemyev, et al., 2019). Thus, QDSSC becomes the better candidate for future generation solar cells.

QDSSC is interesting due to its ability to tune the absorbance by tunning the size of the quantum dots (QDs)(Kusuma & Balakrishna, 2018). The tunability factor can contribute to higher efficiency in capturing the broad range of wavelength of the sunrays. A QDSSC consists of many components such as photoanode, quantum dots, electrolyte, and counter electrode. Component such as photoanode may also affect the QD to produce the optimum PCE. Photoanode act as a medium by collecting and transporting the electron for QDs, thus affecting the photocurrent response (Sharma *et al*., 2016). QDSSC is yet achieved its potential efficiency, experimentally since the maximum PCE of QDSSC that has been reported around 12% (Zhang & Reynoflds, 2019). Thus, it's still remaining a challenge to comprehend the potential of QDSSC.

There are several type of QDs use in the QDSSC such as cadmium sulfide (CdS) (Samadpour et al., 2019), cadmium selenide (CdSe) (Byranvand & Beiranvand, 2013), cadmium telluride (CdTe) (Nideep et al., 2019) and lead sulfide (PbS) (Zhao et al., 2016). CdSe QDs possess the band gap of 1.7eV which possess the absorbance range of visible light region (Kongkanand et al., 2008). CdSe QDs is one of the popular QDs due to its capability of tuning its optical properties (Rezaee et al., 2018). However, there is room of improvement to increase light-harvesting range of CdSe QDs to increase the PCE because it cannot absorb light at the ultraviolet (UV) light region and infrared region.

One of the methods to overcome this problem is by co-sensitizing different semiconductor QDs (Marandi *et al*., 2020). Co-sensitization enable the enhancement of light-harvesting range of solar cells just like a multijunction exciton generation solar cell by incorporating different wavelength material into the solar cells (Z. Du, Artemyev, et al., 2019). One of the studies shows that the co-sensitization of the CdS

and CdSe increase the PCE from 2.5 to 6.8% (Marandi et al., 2020). On the other hand, by incorporating the characteristic of a CdTe QDs into CdSe QDs will improve the PCE of the solar cell (Bang & Kamat, 2009). CdSe/CdTe is one of the co-sensitization QDs that can extending the range of the absorption range of photon wavelength due to the complementary effect of two different range of wavelength (Bhambhani, 2018). In a similar note, the 1st cadmium based ternary alloy such as CdSeTe (Adegoke *et al*., 2015) provide a wider bandgap than CdTe (Chai *et al*., 2016). The wider the bandgap demonstrates the wider of range of photon wavelength (Zhang *et al*., 2016). In a QDSSC, QDs are synthesis on nano-semiconductor. TiO_2 nano-semiconductor is one of the popular semiconductor due to its wide bandgap (H. Tang et al., 1994), ability to provide high surface area for QDs deposition and the ability to increase the carrier lifetimes (Jose *et al*., 2009). Therefore, TiO_2 are used as a photoanode layer for the deposition of QDs. Past research showed that there are many ways to synthesize CdSe/CdTe QDs into the photoanode. CdSe/CdTe co-sensitization has been synthesized using electrochemical atomic layer deposition (ECALD) method (Weixin Li et al., 2015) and successive ionic layer adsorption and reaction (SILAR) (H. Lee et al., 2009).

SILAR method is one of the popular method to deposit QDs on the TiO_2 due to better QDs distribution (Guijarro et al., 2010), good control over QD stoichiometry (P. Yang et al., 2015), easy control the amount of QDs and the average size of QDs deposit on the semiconductor (Jingbo Zhang et al., 2013). However, there are several variations of SILAR method that being implemented in previous research (Becker et al., 2014; Chong et al., 2010; Lu et al., 2015). Different SILAR condition will affect the synthesis of QDs (Jun et al., 2014). Therefore, in this study three variation of SILAR method are being study and compare to one another to understand the effect of variation SILAR method on the deposition of QDs.

On the other hand, the photoelectrode of a QDSSC plays an important role in the deposition of QDs as it can affect the QDs load that change the PCE value of the solar cells (Chetia et al., 2015). Photoelectrode medium such as TiO_2 are widely use due to their good chemical stability (Pan et al., 2018). In this study, TiO_2 nanorods are used as the photoelectrode of the QDSSC. In order to find out the optimum absorbance of CdSe/CdTe co-sensitization QDs, there is a need to find the best cycles for successive ion layer adsorption reaction (SILAR) methods (Y. L. Lee & Lo, 2009). It

is expected that by understanding the QDs synthesis condition, the effect on the efficiency of the CdSe/CdTe co-sensitization QDs can also be estimated.

1.2 Problem statement

CdSe QDs are limited by its absorbance wavelength and cannot absorb light at the ultraviolet (UV) light region and infrared region. There is a need to improve the light harvesting range of CdSe QDs to increase the PCE by optimizing the synthesis and the design of the QDSSC. Co-sensitization of the QDs material have shown promising result in terms of increasing the absorbance range of the QDs. The synthesis condition such as co-sensitizing CdSe with CdTe using SILAR method on the TiO_2 nanorods has yet to be explored. Hence, the parameter of the synthesis method of CdTe as co-sensitized with CdSe on TiO_2 nanorods is of interest for this study.

1.3 Objectives of study

i. To optimize the number of cycles of the SILAR for the growth of CdSe QD on TiO_2 nanorods film.
ii. To synthesize CdSe/CdTe co-sensitizing QDs via SILAR method control by controlling the number of cycles.
iii. To determine the effect of morphology, absorbance, and electrical characteristic of CdSe and CdSe/CdTe QDs sensitized TiO_2 nanorods film.

1.4 Significance of study

The outcome of this study will improve the understanding of synthesis of CdSe/CdTe QDs. The result of this research will assist in the development absorbance range of QDs which lead to the increase PCE. The CdSe/CdTe QDs on the TiO_2 nanorods will provide knowledge on the incorporation of QDs on TiO_2 nanorods and the characteristics of this nanorods structure. The co-sensitization of QDs will provide a better absorption characteristic with a higher light harvesting capability and higher charge recombination resistance that can leads the increase of PCE of QDSSC.

1.5 Research scope

i. The CdSe/CdTe QDs on TiO_2 nanorods film on fluorine doped tin oxide (FTO) glass solar cells will be prepared by using SILAR method with the variable of cycles.

ii. The structural and morphology of the CdSe/CdTe QDs shall be observed by using field emission scanning electron microscope (FE-SEM) and transmission electron microscope (TEM).

iii. The absorbance and electrical characteristic of CdSe/CdTe QDs will be measured using UV-Vis spectrometer, electrochemical impedance spectroscopy (EIS), and solar simulator.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter briefly begins with the general knowledge related to the research followed by current literature on the growth and characteristic of CdSe, CdTe, TiO_2 and quantum dot solar cell (QDSSC). The chapter also discusses the potential of enhancing properties of power conversion rate of CdSe and CdTe. QDSSC based on the results of past research.

2.2 General characteristic of titanium dioxide (TiO_2)

Titanium dioxide also known as titania (TiO_2) uses as decomposition of toxic pollutants (Kim & Yang, 2015), gas sensor (Hamed *et al*., 2016), biomedical application (Esmaeilnejad *et al*., 2019) and solar cell application (Ismail *et al*., 2020). TiO_2 is a good metal oxide for a photoanode due to its band gap and chemical stability (Bhambhani, 2018). The main phases of TiO_2 includes rutile, anatase and brookite (Ghannadi *et al*., 2021). Anatase phase TiO_2 form from lower temperature below 400ºC and rutile phase above 400ºC to 1200ºC. (Anurag *et al*., 2020, Hanaor & Sorrell, 2011, Thamaphat *et al*., 2008). The phase of titanium dioxide can be identified by looking at the crystal bulk structure shown in Figure 2.1. Each of the phase have different crystal size, lattice parameter, density and band gap (Oi *et al*., 2016). Anatase has an energy band gap of 3.23 eV (380 nm) and rutile have the energy band gap of 3.05 eV (415 nm) (Carp *et al*., 2004).

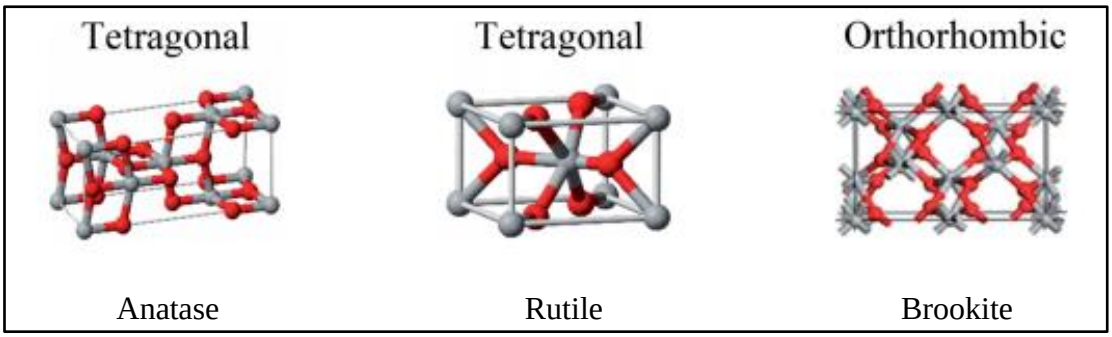

Figure 2.1: Lattice structure of TiO_2 (Oi *et al*., 2016).

Besides the phases of TiO_2, different nanostructure of the TiO_2 also can affect the PCE of QDs. Zhang *et al*., (2016) stated that nanostructure of TiO_2 can affect the loading content of QDs and QDs size distribution leading increase of light harvesting efficiency, facilitate electrolyte diffusion and improved charge collection efficiency due to higher electron diffusion coefficient and longer electron lifetime. TiO_2 can exist in nanowires (NWs) (Sun *et al*., 2018), Nanosheets (NSHs) and nanoparticle (NPs) (Bhambhani, 2018). Table 2.1 shows the previous research of TiO_2 as photoanode.

Table 2.1: Summary of recent research of TiO_2 photoanode.

Photoanode (phase)	Quantum dot-Electrolyte-Counter Electrode	Nanostructure	J_{sc} ($mAcm^{-2}$)	V_{oc} (V)	FF	PCE (%)	Reference
TiO_2 (Anatase)	PbS-S_n^{2-} / S^{2-}-CuS	Nanorods (NRs)	15.8	0.65	0.6	5.6	Latif *et al*., 2020
TiO_2 (Anatase)	CdSe-S_n^{2-} / S^{2-}-Cu_2S	Nanosheets (NSs)	17.0	0.59	0.5	5.0	Zhou *et al*., 2016
TiO_2 (Anatase)	CdSe-ZnS- S_n^{2-} / S^{2-}-Cu2ZnSnS(Se)4	Nanorods (NRs)	17.5	0.56	0.6	6.0	Zhang *et al*., 2016
TiO_2 (Anatase)	CdS/CdSe-ZnS-S_n^{2-} / S^{2-}- Cu_2S	Nanoparticles (NPs)	22.2	0.63	0.5	6.8	Marandi *et al*., 2020
TiO_2 (Rutile)	CdS/CdSe -S_n^{2-} / S^{2-}-Pt	Nanoparticles (NPs)	17.22	0.46	0.3	2.7	C. Chen et al., 2014
TiO_2 (Anatase)	CdSeTe-ZnS-S_n^{2-} / S^{2-}-Cu_2S	Nanoparticles (NPs)	4.4	0.42	0.6	1.1	Esparza et al., 2017
TiO_2 (Anatase)	CdS/CdSeTe-ZnS - S_n^{2-} / S^{2-} - Cu_2S	Nanoparticles (NPs)	4.0	0.58	0.6	1.3	Esparza, Bustos-ramirez, et al., 2017

In this work, TiO_2 nanorods (NRs) is use as the semiconductor photoanode. TiO_2 nanorods possess characteristic such as excellent charge transport ability (C. Chen et al., 2014), excellent charge separation (Thakur et al., 2017), lower grain

boundaries and better pore size distribution (W. Zhang et al., 2016). TiO_2 nanorods have long electron lifetime that increase the effective of photocarrier collection that increase the PCE (B. H. Lee et al., 2009). Compare to nanotube, nanorods have shown greater photoelectron transfer and photo induced performance (J. Chen et al., 2014). Kmentova et al., (2017) shows that TiO_2 nanorods have better photo-electrochemistry (PEC) than TiO_2 nanotube due to NRs able to extend the light absorption to the lower energy region and prolong the electron lifetime.

2.3 General characteristic of cadmium selenide (CdSe)

Cd chalcogenides are widely use as photon-sensitized material for the application of QDSSC (Mingsukang *et al*., 2017). This is because, Cd chalcogenides can exist as a QDs crystalline semiconductor nanoparticle (Jasim, 2015). Cd chalcogenides exist in the form of group II – IV element, which is a popular QDs classes due to its tunability to cover wide range of absorption wavelength (Chaguetmi *et al*., 2020). One of the Cd chalcogenides are cadmium selenide (CdSe). CdSe has an exciton Bohr radius of 10.6 nm with a bandgap energy of 1.74 eV (Jasim, 2015). CdSe exist in zinc blende and wurtzite structure (Naseri *et al*., 2020). CdSe is a metal chalcogenide material with optoelectronic properties that uses for the application of solid-state solar cells, photoconductors, photoelectrochemical cells and solar control coatings, thin film transistors, sensors, lasers, photoconductors, gamma ray detectors (Naseri *et al*., 2020). CdSe is known for its use as QDs, which function as a sensitiser for QDSSC. CdSe QD is shown as a good co-sensitizer material due to their smaller band gap energy (Yang *et al*., 2011). The tunability of Cd and Se forming QDs is in the range of visible region (Reshma et al., 2018). It can be tuned from the wavelength of blue to red colours (Bera et al., 2010). CdSe QDs can absorb sunlight at the highest spectral irradiance region which is in the range of visible light (Ranabhat et al., 2016).

2.4 General characteristic of cadmium telluride (CdTe)

Cadmium Telluride (CdTe) another Cd chalcogenides has an exciton Bohr radius of 15.0 nm with a bandgap energy of 1.50 eV (Jasim, 2015). CdTe QDs have a narrow bandgap with a high conduction bandgap (CB) providing the characteristic for a good QD (Yang & Zhong, 2016). CdTe is also made up of chemical of group 14 and group

16, which called as II-VI group. CdTe QDs is use as optoelectronic device, bio-imaging (Maguire *et al*., 2018) and gamma detector. CdTe material also used as light emitting diodes (LEDs), thin film transistors, laser, photo-detectors and photoluminescent device (Gharibshahi, 2020). CdTe QDs is widely study for the use as a 3rd generation solar cell (Badawi *et al*., 2011). The size of the CdTe QDs is also tuneable by increasing the time for heat treatment using simple chemical synthesis method (Nideep *et al*., 2019). The potential of CdTe was not fully develop as shown in its PCE of the past results (J. Yang & Zhong, 2016).

2.5 Quantum dots

Quantum Dots (QD) is known as the size of the nanocrystals that contain electrons with well-defined, discrete quantum states. In an atom, electron orbits the nucleus in an average distance by columbic attraction. The distance of an electron-hole pair is called exciton Bohr radius. If the particle is small as the Bohr radius, the energy will be confined due to the squeezing of electron hole pair and the energy level will shift (Reshma et al., 2018). Figure 2.2 shows a schematic diagram of the size and energy bandgap of QDs.

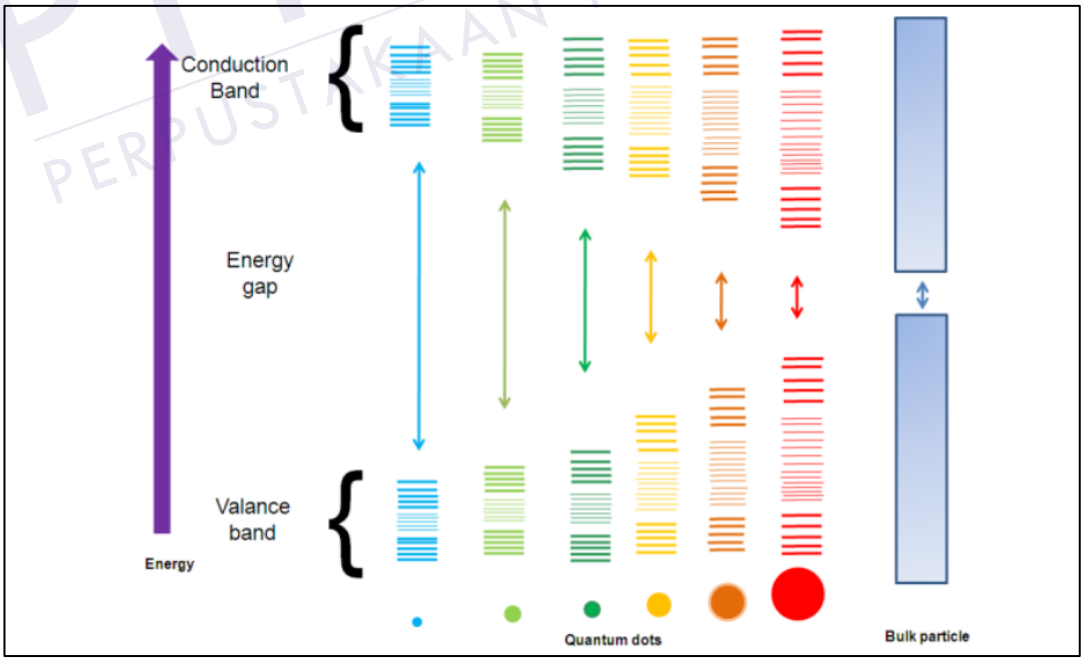

Figure 2.2: Quantum dots and bandgap schematic diagram (Reshma et al., 2018)

The smaller the QDs the more the squeezing of electron hole pair causing higher energy level and shorter wavelength vice versa with larger QDs (Bera et al., 2010). This led to the ability to tune the energy bandgap by controlling the size of the QDs (Han et al., 2020). QDs such as CdSe and CdTe are able to act as photon sensitization, absorbing light and transfer its energy to electricity. Past research work on the use of these QDs grown via various synthesis method and parameter are summarized in Table 2.2.

Table 2.2: Summary of past study regarding CdSe and CdTe QDSSC performance

Material	Substrate	Parameter	J_{sc} (mA/cm^2)	V_{oc} (V)	ff	PCE (%)	Citation
CdTe	TiO_2/FTO	CdTe = 4.40 CdSe = 4.20 CdS = 4.44	0.853 0.932 0.783	0.534 0.545 0.530	0.449 0.429 0.485	0.22 0.25 0.20	Nideep et al., (2020)
CdTe	TiO_2/FTO	C0 minutes C30 minutes C60 minutes C90 minutes C120 minutes	1.25 2.07 3.24 3.5 4.381	0.422 0.403 0.371 0.341 0.190	0.3030 .323 0.439 0.368 0.360	0.16 0.27 0.53 0.44 0.30	Nideep et al., (2019)
CdTe	TiO-FTO	3 hours 6 hours 24 hours 50 hours	0.987 1.035 1.037 1.015	0.405 0.418 0.472 0.495	0.40 0.38 0.37 0.35	0.158 0.167 0.183 0.190	Badawi et al., (2011)
CdSe	TiO_2/FTO	5 cycles 10 cycles	0.0364 0.2584	0.042 0.055	33.76 62.57	0.0027 0.0398	Patel et al., (2016)
CdSe	TiO_2/FTO	1 cycle 2 cycles 3 cycles 4 cycles 5 cycles 6 cycles	1.72 2.66 4.80 6.40 8.47 7.43	0.445 0.501 0.515 0.515 0.493 0.374	0.37 0.38 0.36 0.37 0.36 0.37	0.28 0.51 0.88 1.22 1.50 1.04	Chong et al., (2010)

On the other hand, QDs are connected to the photoelectrode and the electrolyte inside a QDSSC (Mnasri et al., 2020).

2.6 Quantum dots sensitized solar cells (QDSSC)

The working mechanism of the quantum dot sensitized solar cell is identical as a dye sensitized solar cell (DSSC). QDSSC is derived from DSSC by replacing organic dye molecules with quantum dots (QD) as the light harvesting material (Hodes, 2008). The difference between the two is the use of different element to capture the photon energy (Mingsukang et al., 2017). DSSC uses dye as the main source of light absorption, while QDSSC uses QDs. The structure of the DSSC is start with FTO layer, followed by dye

and TiO_2, electrolyte and FTO electrode (Freitag et al., 2017). QDSSC are made up of similar layering starting with the photoanode with the substrate, semiconductor, and quantum dot, followed by the second layer made up of electrolyte and finally counter electrode (Wenhui Li et al., 2020; Marimuthu et al., 2019). Figure 2.3 shows an example of a QDSSC by a combination of QDs-sensitized photoanode, an electrolyte and a counter electrode. The basic working principle of a quantum dot solar cell are when light radiate on the QDSSC, the QD will absorb solar energy and excite the electrons in the valence band (VB). It moves to the conduction band (CB), generate electron-hole pairs (exciton). After that, electrons in the CB of the QDs are ejected into the CB of the TiO_2 forming charge-separation process. The excited electron travelled from the photoanode to the counter electrode. The electrolyte transfers the electrons back to the QDs, thus create a complete circuit.

Each component of a QDSSC is important due to its compatibility to one another. The higher the compatibility the smoother the electron transfer from section to section (Z. Du, Artemyev, et al., 2019). Higher compatibility means the lower the fast charge recombination rate, the higher the PCE (Elibol, 2020). Therefore, there is a need to investigate the importance of each component of QDSSC.

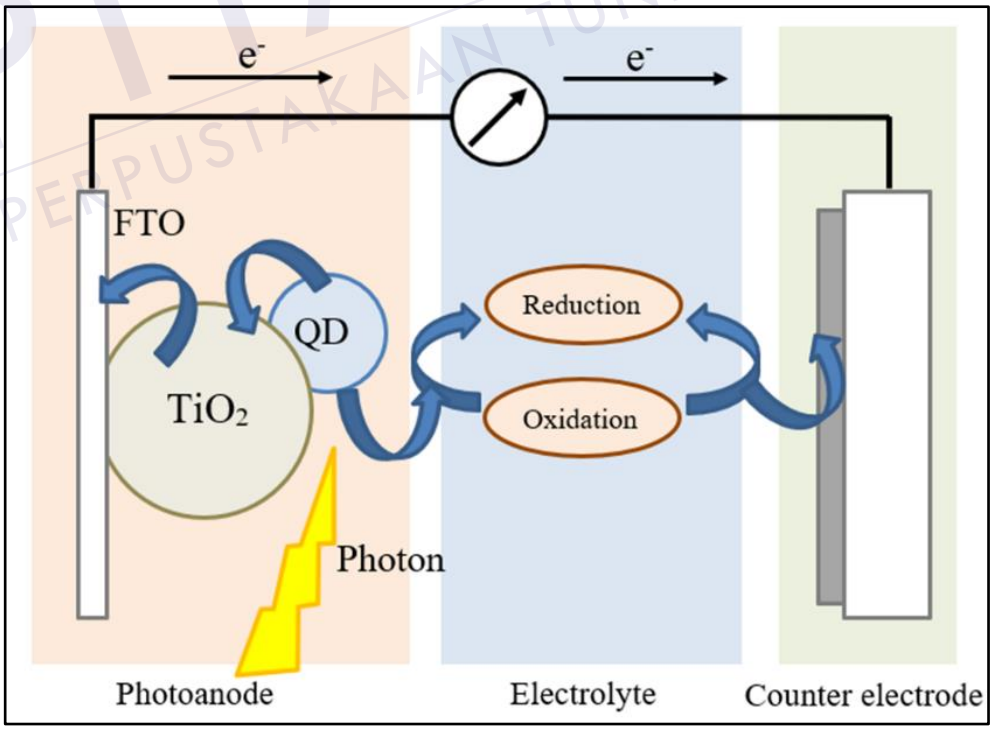

Figure 2.3: An example of a QDSSC

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