### <u>Original Research Article</u> THE OPTICAL-ELECTRO-CHEMICAL PROPERTIES OF CdS/CdSe/ZnS CO-SENSITIZED TiO<sub>2</sub> SOLAR CELLS

#### ABSTRACT

The photovoltaic performance of quantum dot-sensitized solar cell (QDSSC) based on mesoscopic  $TiO_2$  spheres. A series of CdS/CdSe/ZnS co-sensitized  $TiO_2$  photo anodes for QDSSCs were prepared by successive ionic layer adsorption and reaction (SILAR) processes. The growth of CdS, CdSe and ZnS layers were monitored by taking UV–Visible absorption spectra and the SILAR cycles of CdS, CdSe and ZnS show different impact on the performance of QDSSCs. With the deposition times of CdS increasing (from 1 to 5 cycles), the short circuit current density of the device is enhanced. On the contrary, the increasing deposition times of CdSe (from 1 to 5 cycles) has a negative effect for the generation and collection of photoelectron. In addition, the electrochemical impedance spectroscopy technology was used to investigate the impedance of diffusion and recombination in the various devices. Moreover, the effect of SILAR cycles on the recombination resistance was discussed based on the electrochemical impedance spectroscopy results.

Keywords:Solar cells, Quantum dots.

#### 17 I. INTRODUCTION

18 Quantum dot-sensitized solar cells (QDSSCs) are considered as a promising low-cost alternative for 19 third generation photovoltaic [1]. This solar cell is sourcing from the dye-sensitized solar cell (DSSC), 20 which is based on sandwich dye-sensitized nano crystalline work electrode, counter-electrode and 21 electrolyte. Compared to the conversional DSSC, the sensitizer of QDSSC is replaced by semiconductor 22 quantum dots (QDs) such as CdS [2], PbS [3], Ag<sub>2</sub>S [4], CdSe [5], Ag<sub>2</sub>Se [6], CdTe [7] and InAs [8] 23 which possess multiple advantages as tunable band gaps, high extinction coefficient, and high photo 24 stability [9-11]. Unfortunately, QDSSC which promises a high theoretical efficiency up to 44% for its 25 special multi electrons generation character [12], still presents lower energy conversion efficiency and 26 far below the theoretical value. For QD-sensitizers, CdS, CdSe and ZnS have been paid much attention 27 because of their high potential in photo absorption under visible region. The two materials exhibit 28 different characteristics. For CdS, its conduction band (CB) edge is higher than that of TiO<sub>2</sub>, making the 29 electron injection from CdS to TiO<sub>2</sub> very effective, but the absorption range of CdS is too narrow, which 30 restrict the utilization of light. Lee and Lo [13], model system prepared by successive ionic layer 31 adsorption and reaction (SILAR) process is favorable than single CdS or CdSe, which is due to the 32 extension of spectral response in the visible light region and charge injection from QDs to  $TiO_2$ . The 33 influence of SILAR cycles on the device performance has also been investigated recently [14]. However, 34 the detailed optical and especially electrochemical properties of the photo anodes with different SILAR 35 cycles are still lack of deep research. In this paper, we prepared CdS/CdSe/ZnS co-sensitizer on meso porous TiO<sub>2</sub> surfaces with different SILAR cycles. The optical properties of the photo anodes and the 36 37 photovoltaic performance of the corresponding solar cells were investigated. Moreover, electrochemical 38 impedance spectroscopy (EIS) was employed to investigate the interface impedance and chemical 39 capacitance of the cells. Based on the EIS results, the SILAR deposition cycles effect on the charge 40 recombination was discussed.

#### 41 **II. EXPERIMENT**

Materials. Cd(CH<sub>3</sub>COO)<sub>2</sub>.2H<sub>2</sub>O (99%), KCl, Na<sub>2</sub>S, Zn(NO<sub>3</sub>)<sub>2</sub>, Se powder, S powder, Na<sub>2</sub>SO<sub>3</sub>, TiCl<sub>4</sub>,
 TiO<sub>2</sub> paste obtained from Dyesol, Australia.

44 **To prepare TiO<sub>2</sub> films,** the TiO<sub>2</sub> thin films were fabricated by silk-screen printing with commercial 45 TiO<sub>2</sub> paste. Their sizes ranged from 10 to 20 nm. Two layes of film with thickness of 8  $\mu$ m (measured by 46 microscope). Then, the TiO<sub>2</sub> film was heated at 400°C for 5 min, 500°C for 30 min. Afterward, the film

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47 was dipped in 40-mmol TiCl<sub>4</sub> solution for 30 min at  $70^{\circ}$ C and heated at  $500^{\circ}$ C for 30 min. The specific

48 surface area of the mesoporous TiO<sub>2</sub> were investigated by using the N<sub>2</sub> adsorption and desorption

49 isotherms before and after the calcination. The surface area is 120.6  $m^2g^{-1}$  (measured by BET devices).

50 This result indicates that the synthesized material has wider mesoporous structure.

To prepare TiO<sub>2</sub>/CdS/CdSe/ZnS films, the highly ordered TiO<sub>2</sub> were sequentially sensitized with CdS, CdSe and ZnS QDs by SILAR method. First, the TiO<sub>2</sub> film was dipped in 0.5 mol/L Cd(CH<sub>3</sub>COO)<sub>2</sub>-ethanol solution for 5 min, rinsed with ethanol, dipped for 5 min in 0.5 mol/L Na<sub>2</sub>S-methanol solution and then rinsed with methanol. The two-step dipping procedure corresponded to one SILAR cycle and the incorporated amount of CdS QDs was increased by repeating the assembly cycles for a total of three cycles. For the subsequent SILAR process of CdSe QDs, aqueous Se solution was prepared by mixing Se powder and Na<sub>2</sub>SO<sub>3</sub> in 50ml pure water, after adding 1 mol/L NaOH at 70°C for 7h. The TiO<sub>2</sub>/CdS samples were dipped into 0.5 mol/L Cd(CH<sub>3</sub>COO)<sub>2</sub>-ethanol solution for 5 min at room temperature, rinsed with ethanol, dipped in aqueous Se solution for 5 min at 50°C, rinsed with pure water. The two-step dipping procedure corresponds to one SILAR cycle. Repeating the SILAR cycle increases the amount of CdSe QDs (a total of four cycles). The SILAR method was also used to deposit the ZnS passivation layer. The TiO<sub>2</sub>/CdS/CdSe samples were coated with ZnS by alternately dipping the samples in 0.1 mol/L Zn(NO<sub>3</sub>)<sub>2</sub> and 0.1 mol/L Na<sub>2</sub>S-solutions for 5 min/dip, rinsing with pure water between dips (a total of two cycles). Finally, it was heated in a vacuum environment with different temperatures to avoid oxidation (see Fig. 1). The TiO<sub>2</sub>/CdS/CdSe/ZnS was be measured thickness by microscopic. The results of the average thicknessofCdS(1), CdSe(1), ZnS(1) are 40nm, 43.3nm, 40nm respectively.



Figure 1. The diagram shows the instruction of the QDSSCs

**Fabrication of QDSSCs:** The polysulfide electrolyte used in this work was prepared freshly by dissolving 0.5 M Na<sub>2</sub>S, 0.2 M S, and 0.2 M KCl in Milli-Q ultrapure water/methanol (7:3 by volume). The CdS/CdSe/ZnS co-sensitized TiO<sub>2</sub> photoanode and Pt counter electrode were assembled into a sandwich cell by heating with a Surlyn. The electrolyte was filled from a hole made on the counter electrode, which was later sealed by thermal adhesive film and a cover glass. The active area of QDSSC was 0.38 cm<sup>2</sup>.

#### **Characterizations and measurements**

The morphology of the prepared samples was observed using field-emission scanning electron microscopy (FE-SEM, S4800). The crystal structure was analyzed with an X-ray diffractometer (Philips, Panalytical X'pert, CuK $\alpha$  radiation). The absorption properties of the nanotube array samples were investigated using a diffuse reflectance UV–vis spectrometer (JASCO V-670). Photocurrent – Voltage measurements were performed on a Keithley 2400 sourcemeter using a simulated AM 1.5 sunlight with an output power of 100 mW/cm<sup>2</sup> produced by a solar simulator (Solarena, Sweden).

#### 51 III. RESULTS AND DISCUSSION

Detailed morphological features and crystal of the pure  $TiO_2$  and  $TiO_2/CdS/CdSe/ZnS$  photo anodes were investigated using TEM image. A typical TEM image of pure  $TiO_2$  film is depicted in Fig. 2a. It is quite evident that the mean diameter of  $TiO_2$  nanoparticle is about 25 nm. Fig. 2b shows a TEM image of

the TiO<sub>2</sub>/CdS/CdSe/ZnS photo anode prepared with the SILAR cycle number of CdS, CdSe and ZnS at 3, 3 and 2. We can clearly see that QDs uniformly cover the surface of TiO<sub>2</sub> nanoparticles. It shows that the mean diameter of QDs is from 2 nm to 3 nm. The results of the TEM demonstrate that the SILAR method is an efficient TiO<sub>2</sub> sensitization strategy for obtaining well covering the QDs on the TiO<sub>2</sub> surface.







**Figure 3.** (a) UV–Vis absorption spectra of the TiO<sub>2</sub> films sensitized by CdS/CdSe/ZnS QDs shows the light absorption behavior of photoanodes changed with the SILAR cycles of CdS, CdSe and ZnS and (b) Photoluminescence (PL) spectra of the TiO<sub>2</sub>/CdS/CdSe/ZnS.

57 The optical performance of co-sensitized  $TiO_2$  thin films can be monitored by studying the absorbance 58 and energy band gap of the materials. Fig. 3a shows the UV-Vis absorption spectra of thus sensitized 59 electrodes measured after each cycle of SILAR. As expected, the absorbance increased with the 60 deposition cycles of CdS, CdSe and ZnS. However, only absorption spectra with SILAR cycles of the 61 electrode  $TiO_2/CdS(3)/ZdS(2)$  shows the best photovoltaic performance as discussed in the 62 following section. In short-wavelength region (380-550 nm), the increase of absorbance is due to more 63 CdS was loaded on TiO<sub>2</sub> film and the co-absorption of CdS, CdSe and ZnS. In long-wavelength region 64 (550-629 nm), the deposition of higher amounts of CdSe and ZnS on TiO<sub>2</sub>/CdS electrode results in the 65 increase of absorbance. Moreover, the increasing successive deposition cycles also triggers a red shift of 66 absorption spectrum which is due to a slight loss of quantum confinement effect [15]. The evaluated sizes of CdS, CdSe and ZnS are consistent with the sizes measured from the FE-SEM images. The effect 67 68 of deposition cycles of CdS, CdSe and ZnS can be clearly seen on the energy band gap values of 69 CdS/CdSe/ZnS co-sensitized TiO<sub>2</sub> films. The estimated band gaps vary from 1.97 eV to 2.7 eV, which

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70 are higher than the values reported for CdS and CdSe in bulk (2.25 eV and 1.7 eV [1], respectively), 71 indicating that the sizes of CdS, CdSe and ZnS on TiO<sub>2</sub> films are still within the scale of QDs. A higher 72 absorption is thus obtained because the absorption spectrum of ZnS complements those of the CdSe and 73 CdS QDs. Furthermore, ZnS acts as a passivation layer to protect the CdS and CdSe QDs from photo 74 corrosion [16]. Fig 3b shows the PL of different photoanodes that their thick is changed by the cycles 75 SILAR. After the CdS, CdSe, and ZnS QDs are sequentially deposited onto the TiO<sub>2</sub> film, a cascade type 76 of energy band structure is constructed for the co-sensitized photo anode. The best electron transport 77 path is from the CB of ZnS and CdSe to that of CdS, and finally, to TiO<sub>2</sub> film (shows Fig 6b). Thus, the 78 PL of TiO<sub>2</sub>/CdS/CdSe/ZnS was quenched (displayed in Figure 3b). This reveal that TiO<sub>2</sub> film serve as 79 effective quenchers of excited CdS, CdSe and ZnS QDs. The thick photo anode film quenches more 80 efficiently than thin photo anode film.



**Figure 4.** (a) XRD and (b) Energy dispesive X - ray spectrum (EDS) of TiO<sub>2</sub>/CdS/CdSe/ZnS photo anodes.

The structure of the TiO<sub>2</sub>/QDs photo electrodes for photovoltaic applications, shown in Fig. 4(a), are studied by the XRD patterns. It reveals that the TiO<sub>2</sub> have a anatase structure with a strong (101) peak located at 25.4°, which indicates that the TiO<sub>2</sub> film are well crystallized and grow along the [101] direction. Three peaks can be observed at 26.4°, 44° and 51.6°, which can be indexed to (111), (220) and (331) of cubic CdS, CdSe respectively. Two peaks can be observed at 48° and 54.6°, which can be indexed to (220) and (331) of cubic ZnS respectively. It demonstrates that the QDs have crystallized onto the TiO<sub>2</sub> film. Fig. 4(b) is the raman spectrum of the TiO<sub>2</sub>/QDs photo electrodes. It shows that an anatase structure of the TiO<sub>2</sub> films have five oscillation modes correspond to wave number at 143, 201, 395, 515 and 636 cm<sup>-1</sup>. In addition, two peaks can be observed at 201, 395, and 515 cm<sup>-1</sup>, which can be indexed to the cubic structure of CdS, CdSe. The results of the raman is likely the results of XRD. Fig. 4 (b) is the energy dispersive X ray spectrum of the TiO<sub>2</sub>/CdS/CdSe/ZnS film. It shows that the Ti and O peaks are from the TiO<sub>2</sub> film, Cd, Se, Zn and S peaks, clearly visible in the EDS spectrum, are from the QDs. The Si is from the FTO and C is from the solvent organic. That shows, the QDs are well deposited onto the TiO<sub>2</sub>.



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Figure 5. (a) The J–V curves of the QDSSCs with different photoanodes under one sun illumination and (b) diagram shows the values efficiency of solar cells.

85 In order to understand the effects of SILAR cycles of CdS, CdSe and ZnS, we prepared a series of combinations of CdS, CdSe and ZnS QDs on TiO<sub>2</sub> films, investigated their photovoltaic performances 86 87 with polysulfide electrolyte. All the samples were coated with ZnS to inhibit the recombination at the 88  $TiO_2$  photo anode/polysulfide electrolyte interface [17]. Fig. 5a presents the photocurrent density voltage 89 characteristics of the QDSSCs with different CdS/CdSe/ZnS co-sensitized TiO<sub>2</sub> films (active area of 90 0.38 cm<sup>2</sup>) at AM 1.5 (100 mW/cm<sup>2</sup>), and the related parameters of these QDSSCs are listed in Table 1. 91 Fig. 5a shows that the power conversion efficiencies of QDSSCs are increasing with the SILAR cycle 92 number of CdS, CdSe and ZnS at 3, 3 and 2, respectively. It is noted that lower power conversion 93 efficiency was obtained for those cells with either less CdS and CdSe SILAR cycles than 3 or more CdS 94 and CdSe SILAR cycles than 3 (shows Fig 5b). The TiO<sub>2</sub>/CdS(3)/CdSe(3)/ZnS(2) device shows an 95 open-circuit voltage (V<sub>oc</sub>) of 0.76 V, a short-circuit current density (J<sub>sc</sub>) of 4.79 mA/cm<sup>2</sup>, fill factor (FF) 96 of 0.41 and an energy conversion efficiency ( $\eta$ ) of 1.52%. When the deposition cycles of CdS and CdSe 97 increase, slightly changes in  $V_{oc}$  and FF values were obtained. Remarkably, the  $J_{sc}$  decreases, which 98 result in a substantial reduce of  $\eta$  (from 1.52% to 0.45%). These results indicate that although better light 99 absorption performance were obtained when more CdSe loaded on TiO2/CdS, the excessive CdSe on 100  $TiO_2/CdS$  films may lead to an increase of recombination in photo anodes. On the contrary, the increase 101 of ZnS leads to the increasing generation of photoelectron and is helpful to collect excited electrons from 102 ZnS, CdSe and CdS to TiO<sub>2</sub> film.

103  $J_{SC}$  is given by equation:

### $J_{SC} = q \int b_s(E)QE(E)dE \tag{1}$

104 Therebs(E) is the photon current density, is the number of photons in the rangeEtoE+dEper unitareaper 105 unittime. qis thecharge of the electron, QEdepends on the absorption coefficient of the materialsolar cell. 106 The short-circuit current depends on a number of factors: the area of the solar cell, the number of 107 photons, the spectrum of the incident light, the optical properties (absorption and reflection) and the 108 collection probability of the solar cell, which depends chiefly on the surface passivation and the minority 109 carrier lifetime in the base. From Equation 1, we see that the  $J_{SC}$  is not directly dependent on the thickness of 110 thelayer of QDs. When the thickness of the layer of QDschanges, the results change the absorption spectrumandthe collection probability of the solar cell. After all, they cause change of J<sub>SC</sub>, 111 112 however, this change is nonlinear.

113 An equation for  $V_{oc}$  is found by setting the net current equal to zero in the solar cell equation to give:

$$V_{OC} = \frac{kT}{q} ln \left(\frac{I_L}{I_0} + 1\right) \qquad (2)$$

114 The above equation shows that  $V_{oc}$  depends on the saturation current of the solar cell and the light-generated current. The saturation current, I<sub>0</sub> depends on recombination in the solar cell. 115 Open-circuit voltage is then a measure of the amount of recombination in the device. FF depend on  $V_{OC}$ 116 117 values, the junction quality (related with the series  $R_s$ ) and the type of recombination in a solar cell. From 118 Table 1, V<sub>oc</sub>valueschangeaccording to thefilm thicknessfrom0.29to0.76, corresponding to the change 119 inFFfrom0.26to0.41. Therefore the FF is the low value because  $V_{OC}$  is low. On the other hand,  $V_{OC}$ 120 depend on the recombination process, particularly they are large, it gives low open-circuit voltages. In 121 addition, FF is effected by R<sub>s</sub>. The equations of R<sub>s</sub> can be calculated by Thongpron and co-workers [18].

$$R_{s} = \frac{V_{1} - V_{2}}{I_{2} - I_{1}} - \frac{1}{\lambda(I_{2} - I_{1})} \ln[\frac{I_{ph} + I_{o} - I_{1}}{I_{ph} + I_{o} - I_{2}}] \quad (3)$$

122 Two operating points (I<sub>1</sub>, V<sub>1</sub>) and (I<sub>2</sub>, V<sub>2</sub>) on a single I-V curve.  $\lambda = \frac{q}{nKT}$ ; I<sub>ph</sub>, I<sub>o</sub> are the

123photocurrent and the diode reverse saturation current.  $R_s$  values are calculated from 55 to 158 mΩcm<sup>2-</sup>.124This values is large as result as low FF.

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Table 1. Photovoltaic performance parameters of QDSSCs based on different photo anodes <sup>a</sup>.

No	Samples	J <sub>SC</sub> (mA/cm <sup>2</sup> )	V <sub>OC</sub> (V)	Fill factor FF	Efficiency η(%)
1	TiO <sub>2</sub> /CdS(1)/CdSe(3)/ZnS(2)	2.18(±0.013)	0.29(±0.001)	0.35(±0.0011)	0.22(±0.009)
2	$TiO_2/CdS(2)/CdSe(3)/ZnS(2)$	4.28(±0.05)	0.54(±0.012)	0.37(±0.013)	0.86(±0.031)
3	$TiO_2/CdS(3)/CdSe(3)/ZnS(2)$	4.79(±0.01)	0.76(±0.035)	0.41(±0.031)	1.52(±0.022)
4	$TiO_2/CdS(4)/CdSe(3)/ZnS(2)$	5.73(±0.011)	0.39(±0.019)	0.31(±0.02)	0.68(±0.013)
5	TiO <sub>2</sub> /CdS(5)/CdSe(3)/ZnS(2)	3.05(±0.013)	0.45(±0.050)	0.32(±0.045)	0.45(±0.037)
6	$TiO_2/CdS(3)/CdSe(1)/ZnS(2)$	6.05(±0.02)	0.356(±0.055)	0.256(±0.05)	0.55(±0.045)
7	TiO <sub>2</sub> /CdS(3)/CdSe(2)/ZnS(2)	4.21(±0.035)	0.55(±0.013)	0.38(±0.011)	0.88(±0.023)
8	TiO <sub>2</sub> /CdS(3)/CdSe(4)/ZnS(2)	3.30(±0.017)	0.48(±0.019)	0.31(±0.021)	0.50(±0.011)
9	TiO <sub>2</sub> /CdS(3)/CdSe(5)/ZnS(2)	2.08(±0.015)	0.33(±0.03)	0.27(±0.037)	0.18(±0.022)
10	$TiO_2/CdS(3)/CdSe(3)/ZnS(1)$	7.03(±0.014)	0.39(±0.01)	0.26(±0.2)	0.73(±0.162)

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<sup>*a</sup>The standard deviation is based on the data of three cells.*</sup>

135 The TiO<sub>2</sub>/CdS/Cdse/ZnS co-sensitized solar cells demonstrated a better performance (1.52%) than the TiO<sub>2</sub>/CdS (0.92%) and TiO<sub>2</sub>/CdSe QDSSC (0.31%) [19]. This suggests that the charge injection from 136 the CdSe conduction level to the TiO<sub>2</sub> conduction level may not be effective, due to the quasi Fermi 137 138 levels of CdSe being lower than that of TiO<sub>2</sub> [13]. However, the quasi Fermi level of CdS quantum dots 139 is higher than that of the  $TiO_2$  layer [20] and it is expected to improve the charge injection from CdSe to 140 TiO<sub>2</sub>. Moreover, A ZnS coating forms a potential barrier between the QDs and the electrolyte, which 141 blocks the electrons in the CB from recombination with the electrolyte [21]. Resulting in a high performance of efficiency. Because the CdS Fermi energy level position is higher than of TiO<sub>2</sub>, 142 143 beneficial effects are conferred to the coupled QDSSC system. From Table 1, it is evident that the 144 photocurrent density of the coupled QDSSC was influenced by CdS/CdSe/ZnS co-sensitization cycles 145 [22], which can be explained in two ways. First, particle size variation in CdS, CdSe and ZnS QDs leads 146 to the quasi Fermi level alignment and consequently, results in cascade energy level structure in the 147 order of TiO<sub>2</sub><CdS<CdS<ZnS. That is, the introduction of a CdS layer between TiO<sub>2</sub> and CdSe elevates 148 the conduction band edge of CdSe, giving a higher driving force for the injection of excited electrons out 149 of the CdSe layer [20]. Second, the photocurrent density might be enhanced with QDs loading by means 150 of increasing coating cycles [23].



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 $C = 10.0 \mu f$ 

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 $C = 23.1 \, \mu F$ 





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Figure. 6. (a) Nyquist impedance plots of EIS spectra measured under dark condition for 166  $TiO_2/CdS(3)/CdSe(3)/ZnS(2)$  QDSSCs, the measurement was performed at a negative bias of 0.7 V. (b) Bode curve 167 and (c) the proposed energy band structure of the TiO<sub>2</sub>/CdS/CdSe/ZnS nanostructure interface. All energy levels are 168 based on the normal hydrogen electrode scale. CB and VB are the conduction band and the valence band, respectively [15].

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170 In order to reveal the micro mechanism of the QDSSCs, EIS has been carried out under dark 171 conditions at varying negative applied bias (0.7–0 V). Figure 6a shows the Nyquist plots of the 172 CdS(3)/CdSe(3)/ZnS(2) QDs - sensitized solar cells. We find two semicircle of the EIS spectra at high 173 frequency and low frequency. The small semicircle at high frequency corresponds to the resistance 174 movement of particles at interface of counter electrode/electrolyte ( $R_{etl}$ ) and FTO/TiO<sub>2</sub> interface. The 175 large semicircle at low frequency from 10-100 kHz described resistance against the movement of 176 electron in the semiconductor  $TiO_2$  and the charge recombination resistance at the  $TiO_2/QDs$ /electrolyte 177 interface  $(R_{ct2})$  and against inside the diffusion in of electrolyte  $(Z_w)$ . From Figure 6a we see the value 178  $R_{cl2}$  near 200 $\Omega$  defined large, so it causes resistance the movement of electrons at the interface of 179  $TiO_2/ODs/electrolyte$  and causes recombination of the electrons and polysulfide [22]. Figure 6b shows 180 the Bode plot of the QDSSC with TiO<sub>2</sub>/CdS(3)/CdSe(3)/ZnS(2) photo anode that is illuminated with an 181 1000W/m<sup>2</sup>. At low frequency peaks corresponds to the movement of electrons at the interface 182  $TiO_2/QDs$ /electrolyte, while the peak at higher frequencies to describe the movement of the particles at 183 the interface Pt/electrolyte. Lifetime of electrons in semiconductor ( $\tau_e$ ) is determined by the following 184 formula =  $1/2\pi f_{max}$ . The  $f_{max}$  is the peak of the Bode plot at low frequencies,  $\tau_e \sim 1.77$ ms.

#### **IV. CONCLUSIONS** 185

186 We have successfully fabricate solar cells based on photo anodes which is sequentially modified with 187 CdS, CdSe, and ZnS QDs. A series of the CdS/CdSe/ZnS co-sensitized TiO<sub>2</sub> photo anodes for QDs 188 sensitized solar cells were prepared by successive ionic layer absorption and reaction (SILAR) 189 processes. We have evaluated the number of CdS, CdSe and ZnS SILAR cycles effect on the optical and 190 electrochemical properties of the cells. The increasing SILAR cycles of both CdS, CdSe and ZnS lead to 191 an increase in the light absorption, but show different impacts on the performance of QDSSC. This 192 improvement is mainly attributed to the overlap of the absorption spectra of the different materials and 193 the formation of an ideal stepwise band structure which promotes the transport of excited electrons and 194 holes across the composite electrode. The synthesized TiO2/CdS/CdSe/ZnS photo anode exhibits a 195 maximum efficiency value of 1.52%.

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