Investigating the effect of different quantum dots on the absorption spectrum and characteristics of quantum dot sensitized solar cells

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Abstract

Quantum dot sensitized solar cells are one of the new generation of solar cells that have attracted much attention. Theoretical and simulation studies have predicted high efficiency for these cells so that in the future these cells could be a good alternative to silicon solar cells. Other advantages of these cells are their ease of fabrication and cheaper manufacturing methods than existing cells. The main idea of this paper is to investigate the effect of different quantum dots on the optical and electrical characteristics of these cells and in particular the efficiency. We then examined the effect of simultaneous sensitizing by different quantum dots and we observed that the cell's light absorption as well as the efficiency in simultaneous sensitizing increased. Then one of the cells that gave the best simulation results was studied experimentally and the light absorption, efficiency and other characteristics were obtained. Further, the effect of cobalt sulfide as the counter electrode in this cell, instead of platinum and gold, has been investigated and it has been found that the efficiency has increased.

1 Introduction

The solar power that gets to earth is estimated to be about 120,000 terawatts [4]. This electromagnetic energy can be transformed into other useful forms of energy such as heat, electricity and chemicals to supply human daily energy. Reports have shown that using solar cell by 10% efficiency in just 0.1% of the earth surface can provide current electricity demand [5]. The first-generation solar cells were based on silicon and then the thin-layer solar cells were made as second-generation. The production of solar cells with high energy efficiency and low cost, in order to mass produce and improve energy storage facilities, is a priority of research in solar cells. By combining the knowledge of first and second generations of solar cells, a plan has been developed for the third generation of solar cells that can be used to achieve Shockleys extraordinary theoretical efficiency while reducing cell manufacturing costs [20].

Quantum dot solar cells are a bunch of solar cells based on nanomaterials and quantum dots (QDs) and QDs can be used in a variety of solar cells to reduce costs and increase
efficiency. The optical behavior of quantum dots is such that they emit visible light of varying wavelengths when exposed to ultraviolet light [14]. The point is that the wavelength of light emitted from quantum dots depends on the size of the quantum dots. In smaller quantum dots, the band gap is larger; therefore, by applying the UV beam to smaller quantum dots, the electrons travelling to the higher energy band emit a larger energy band-gap when losing excess energy and return to steady state and beam of visible light they emit has more energy and is bluish. Quantum dots have attracted attention of researchers for making solar cells because of their their adjustable band-gap to their desired size, so their absorption spectra can be adjusted to the spectral distribution of sunlight [22], their high extinction coefficient [10], rapid separation of charges due to the large intrinsic dipole moments of them [28] and their ability to produce multiple excitons by absorbing a single photon causes the incident photon to current conversion efficiency be more than 100% [2].

If the photon energy exceeds the threshold required for impact ionization, this extra energy will excite another electron and produce another exciton [26]. Impact Ionization is a process in which an electron or hole with sufficient kinetic energy can excite one electron from the valence band to the conduction band resulting in the production of another electron-hole pair.

Quantum dot sensitized solar cells (QDSSCs) are a replacement of dye sensitized solar cell (DSSCs) [16]. Difference between QDSSCs and DSSCs is sensitizers which are responsible for absorbing light. In DSSCs the sensitizers are organic dye molecules or metal-organic compounds and in QDSSCs they are sensitize with quantum dots. briefly, the operation principles of these cells are as follows.

After the light is emitted into the photovoltaic cell, the quantum dots on the surface TiO$_2$ layer absorb light, which excites the quantum dot electrons from the valance band to the conduction band. This leaves a positive charge hole in the vacancy of the electron. The generated electron-hole pair (exciton) at the boundary of the quantum dots with TiO$_2$ must be separated. The excited electron is transferred to the TiO$_2$ electrode and transferred to the counter electrode through an external circuit. In addition, through electrolyte which plays the role of oxidation /reduction (redox) pair, the electron transfers to the Ground state of the quantum dots and becomes oxidized. Then the intermediate undergoing the oxidation process goes through the diffusion process to the counter electrode and is then subjected to the reduction process again.

Selecting the counter electrode is one of the key points in achieving high efficiency. Because the counter electrode plays the role of oxidation , it is necessary to select the counter electrode from materials with low resistance and high work function. Mainly in quantum dot sensitized solar cells, the S$^{2-}$/S$_x$ is redox pair and the platinum, gold and cobalt sulfide are used as the counter electrode.
2 Simulation method

If the wavelength of the incident light is less than or equal to the size of the structure, we will no longer be able to use the ray optics analysis methods for obtaining accurate solutions. Therefore, we will need a new optical method to provide the correct and expected response. For optical simulation we used the method Finite-difference time-domain (FDTD) because this method can solve Maxwell’s equations directly in the time domain, thereby providing accurate broadband solutions to electromagnetic wave propagation and scattering problems [1]. This is a vector-based approach that provides users with information about frequency and time domains and provides a different perspective on issues and applications in electromagnetism and photonics. The FDTD method has been one of the successful methods that does not use matrix inversion and due to its purely computational nature, the FDTD is free from linear algebra problems that limit other frequency domain analysis methods to one million unknowns. Hence, models with one billion unknowns are implemented for FDTD and in theory there is no high limit on the number of unknowns. The sources of error in the FDTD method are well known and can be reduced for more accurate answers. Therefore, only a single run of the simulation can achieve a system frequency response over a wide range. The FDTD method is a systematic one, and the analysis of a new structure is reduced to a networking problem by this method, and no need to rewrite complex integral equations [25].

As the name implies, the time domain finite difference method is done in the time domain. So when a simulation is run, the Maxwell equations are in fact solved in the time domain to obtain E(t) and H(t). In FDTD Method we solve the Maxwell’s equations by dividing the electric and magnetic fields, which are initially continuous functions of time, and obtain the fields in time \( \Delta t \) that we briefly represent with n using step-time equations (see Eqs (1) and (2) [27]).

\[
\vec{E}^{(n+1)} = \vec{E}^{(n)} + \frac{\Delta t}{\varepsilon} \vec{\nabla} \times \vec{H}^{(n+\frac{1}{2})}, \tag{1}
\]

\[
\vec{H}^{(n+\frac{3}{2})} = \vec{H}^{(n+\frac{1}{2})} - \frac{\Delta t}{\mu} \vec{\nabla} \times \vec{E}^{(n+1)}. \tag{2}
\]

In this equation, \( \varepsilon \) is the electrical permittivity and \( \mu \) is magnetic permeability. Using Eqs (1) and (2) and having the primary electric field, we can calculate the final value of the electric and magnetic fields. But most of the time we are looking for an electric field in terms of frequency. To obtain a single-phase or continuous-wave field in steady state, it should be obtained from the electric field in terms of the Fourier transform time during the simulation as Eq.(3) [27]. Consequently, by taking the Fourier transform of the electric field in the time domain during the simulation, the electric field will be obtained at any particular frequency or equivalent at any particular wavelength.

\[
\vec{E}(\omega) = \int_0^T e^{j\omega t} \vec{E}(t) dt. \tag{3}
\]

Eq.(4) can also be used to calculate the power absorbed by the cell per unit volume
per frequency \[6\]. To calculate it, we only need to know the electric field intensity and the imaginary part of the electrical permittivity of the material.

\[
P_{\text{abs}}(r, \omega) = -0.5 \times \omega |E|^2 \text{Im}(\varepsilon)
\]

(4)

The number of photons absorbed per unit volume per frequency can be calculated by dividing the absorption power in that frequency by the energy of each photon in the same frequency by Eq. (5) \[27\].

\[
g = \frac{P_{\text{abs}}}{\hbar \omega} = -\frac{0.5 \times |E|^2 \text{Im}(\varepsilon)}{\hbar}
\]

(5)

If we assume each absorbed photon produces an electron-hole pair, the rate of electron-hole production \((G)\) can be obtained by integrating Eq. (5) over the entire simulated spectral region \[27\].

\[
G = \int_{\text{solar spectrum}} gd\omega = \int_{\text{solar spectrum}} \frac{-0.5 \times |E|^2 \text{Im}(\varepsilon)}{\hbar} d\omega
\]

(6)

By solving the equations of drift and diffusion for carriers, given separately for electrons and holes by Eqs. (7) and (8), and by considering the continuity equations, the production rate and the recombination rate for each carrier, we can obtain voltage-current diagram of solar cells \[27\].

\[
J_n = q\mu_n nE + qD_n \nabla n,
\]

(7)

\[
J_p = q\mu_p pE - qD_p \nabla p.
\]

(8)

In these equations \(q\) represents the electrons charge, \(\mu_n\) and \(\mu_n\) are the mobility of electrons and holes, \(n\) and \(p\) are the densities of electrons and holes, respectively. \(E\) is electric field, \(D_n\) and \(D_p\) are the diffusion coefficients of electrons and holes, respectively. Efficiency can then be calculated using Eq. (9) \[13\]:

\[
\eta = \frac{J_{SC} \times V_{OC} \times FF}{P_{\text{in}}}
\]

(9)

Where \(P_{\text{in}}\) is the power intensity of the incident light (100 \(mW/cm^2\)) and Fill Factor \(FF\) is defined by Eq. (10) \[13\].

\[
FF = \frac{P_{\text{max}}}{J_{SC} V_{OC}}
\]

(10)

\(P_{\text{max}}\) is the maximum power of a photovoltaic cell, \(J_{SC}\) is short circuit current density and \(V_{OC}\) is open circuit voltage.

### 2.1 The purpose of simulating solar cells

With the goal of reducing production costs and increasing the efficiency of solar cells, research on solar cells is increasingly focused on new solar cell design concepts, including nanostructured solar cells. Solar cell simulation is necessary to predict the behaviour of...
these devices. As the complexity of the design of photovoltaic cells increases, it becomes difficult to obtain analytical solutions to describe their performance. In a real cell, non-ideal processes such as surface and volume recombination of carriers reduce the efficiency of solar cells. A combination of optical and electrical simulations that considers these non-ideal processes is essential to more accurately simulate solar cells.

2.2 Simulation of the effect of quantum dot type on absorption and electrical characteristics of QDSSCs

The usual structure of these cells is FTO / TiO$_2$ / QDs / electrolyte / counter electrode as shown in the Fig. 1. The active area of these cells includes TiO$_2$ and quantum dots. Quantum dots are the major absorbers of sunlight and excitons are produced after absorbing light using QDs. Photocurrent is formed by the transfer of electrons to the TiO$_2$ anode [11]. Based on the previously described relationships, we simulated the solar cells with different sensitizers.

For quantum dot sensitized and dye sensitized solar cells, the best TiO$_2$ layer thickness is 10$\mu$m [19]. We optimized the TiO$_2$ layer thickness for all QDSSCs, which we discuss in simulation section, to get the most efficiency. The result is shown in Fig. 2 which confirms the access to the highest efficiency at approximately 10$\mu$m.

Although the open circuit voltage is linearly correlated with the thickness of this layer and the absorption of the cell will increase with increasing thickness, but when the thickness of the TiO$_2$ layer increases, the carrier recombination rate increases and the short circuit current drops sharply. Which has a negative effect on cell efficiency. In the simulation, we consider the layer thickness 10$\mu$m and discuss the effect of different quantum dots as sensitizer on the cell characteristics.

We performed the calculations to obtain the absorption spectrum of cells according to the described equations and the absorption spectrum of QDSSCs with different quantum dots in wavelengths between 300 nm and 110 nm are shown in Fig. 3. Among these nanomaterials, PbS and PbSe can greatly increase the rate of electron-hole production due to the expansion of the absorption band towards the infrared region. Thus, the current density of cells using these materials should be more than other cells.

As can be seen in the diagram of the current density-voltage of these cells (see Fig. 4),
Figure 2: Cell efficiency changes based on TiO$_2$ layer thickness.

Figure 3: The absorption spectrum of the active area of solar cell.
the PbSe and PbS quantum dots have low $V_{OC}$ despite their very good light absorption, due to the low band-gap. The CdTe, CdS and CdSe quantum dots have higher $V_{OC}$ due to the higher band-gap and thus the accumulation of more energetic electrons.

The cells characterization results are summarized in Table 1 which shows that CdSe has the highest efficiency.

### 2.3 Co-sensitized solar cells

By using two types of QDs, absorption and efficiency of the solar cell can be controlled by two substances. We performed the calculations to obtain the absorption spectrum of co-sensitized solar cells with different pairs of QDs and the absorption spectrum of them in wavelengths between 300 nm and 110 nm are shown in Fig. 5. By comparing the Fig. 3 and Fig. 5 it can be concluded that using two different sensitizers, one of them is selected from compounds with small band-gap and the other from compounds with larger band-gap, it increase the absorption of the cell.

It has been shown experimentally that in sensitized TiO$_2$ single crystals by PbS, when the polysulfide electrolyte is used, photocurrent has a quantum efficiency greater than one
Figure 5: The absorption spectrum of co-sensitized solar cells

Table 2: Results of characterization of current density-voltage curves of co-sensitized solar cells

| Sensitizers | $J_{SC} (mA/cm^2)$ | $V_{OC} (V)$ | $\eta (%)$ | FF |
|-------------|--------------------|---------------|-------------|----|
| PbSe / CdS  | 18.8               | 0.6           | 10.4        | 0.9|
| PbS / CdSe  | 20.9               | 0.8           | 14.3        | 0.9|
| PbSe / CdSe | 21.6               | 0.7           | 13.0        | 0.8|
| PbS / CdS   | 20.5               | 0.9           | 15.5        | 0.8|

However, as mentioned, the cell made only with this material has low $V_{OC}$. The characterization results for co-sensitized cells are summarized in Table 2 which shows that the PbS/ CdS sensitized solar cell has higher $V_{OC}$ than PbS sensitized solar cell. Fig. 6 shows the current density-voltage of cells sensitized by two types of quantum dots.

In co-sensitized solar cells, that one type of QDs is selected from the PbS and PbSe compounds to increase the rate of carrier production by extending the absorption range to the infrared region and the other type is selected from compounds by band-gap more than 1 eV in order to improve the $V_{OC}$ in addition to increasing the absorption at shorter wavelengths, can achieve higher efficiency than sensitized solar cells with one type of quantum dot. Our simulation results show the highest efficiency for sensitized cell using PbS and CdS, so we chose this cell for the experimental section.
3 Experimental methods

3.1 Anode preparation

FTO (Fluorine-Tin-Oxide (FTO) Coated Glass Plates; sheet resistance \(8\Omega/\square\)) were used as substrates and pretreated by rinsing in an ultrasonic bath of detergent and acetone for 10 and 20 minutes in turn, then rinsing with a large amount of deionized water and ethanol, and at last dried with nitrogen gas. Transparent titanium dioxide (TiO\(_2\)) paste was applied to substrates using the doctor-blade method. TiO\(_2\) nanoparticles were in anatase phase with average size of \(20 - 25\) nm. The nanoporous nature of the TiO\(_2\) layer provides high surface area which can increase the QDs adsorption and then high photocurrent generation. After application of transparent TiO\(_2\) paste, the substrates were heated at \(120^\circ\)C for 0.5 h. Reflective anatase TiO\(_2\) paste after that was applied on previous layer by the same method and the deposited photoanodes were heated at \(450^\circ\)C for 0.5 h. This material provides a high scattering layer as reflector that increases light harvesting and photocurrent.

For deposition of PbS and CdS quantum dots on TiO\(_2\) electrode we used successive ionic layer adsorption and reaction (SILAR) method. The electrode first dipped in a 0.02 M Pb(NO\(_3\))\(_2\) aqueous solution for 30 s, rinsed with deionized water and then dipped in 0.02 M Na\(_2\)S aqueous solution for another 30 s followed by rinsing which was termed as one SILAR cycle. The next step is the deposition of CdS quantum dots. Similarly, for the CdS nanoparticles layer, the electrode first dipped in a 0.2 M Cd(NO\(_3\))\(_2\) aqueous solution for 5 min, rinsed and then dipped in 0.2 M Na\(_2\)S aqueous solution for another 5 min.

The size of quantum dots can be controlled by the number of immersion cycles. The method is designed to increase the particle size of a monolayer during an immersion cycle. The optimal number of cycles can be obtained by repeating the experiment several times to maximize cell efficiency. In this study, layers with different cycles were used to sensitize the TiO\(_2\) electrode once only with PbS quantum dots, once only with CdS quantum dots.
and then by combining two types, with PbS/ CdS order as hybrid samples. Four sensitized electrode specimens were thus obtained for use in cell fabrication.

### 3.2 Electrolyte preparation

In dye-sensitized solar cells, platinum is typically used as the counter electrode and $I^-/I_3^-$ as the oxidation / reduction pair, but unfortunately the well-known pair of $I^-/I_3^-$ is not compatible with low band-gap semiconductors and lead to rapid corrosion of these materials [17]. For QDSSCs, other pairs such as cobalt compounds ([cobalt(o-phen)$_3^{2/3}$]), ferrocene / ferrocinium and polysulfide ($S^{2-}/S_x$) seem to work well [18, 24]. Although cobalt compounds are suitable for low energy band-gap semiconductors, this is good for low light intensity cases and has a negative effect on cell function in high light intensity cases.

Polysulfide electrolyte were prepared by mixing suitable quantities of Na$_2$S, S and KCl powders in 3:7 water/methanol solution. Then we put it on the magnetic stirrer for two hours to obtain a uniform solution. The color of the solution changes from yellow to orange after stirring.

### 3.3 Counter electrode

Different materials and different deposition methods were used to prepare the counter electrodes. For this purpose, the FTO is being washed in the same way as in the preparation of the substrates described above. The method for deposition of Pt and Au was physical vapour deposition (PVD) at pressure of $10^{-5}$ millibars and the thickness of deposited layer was of 100 nm. Another approach was to use CoS nanoparticles, which we applied to the pre-prepared FTOs using SILAR method. The counter electrodes were prepared by first dipping a clean FTO in 0.5M Co(CH$_3$COO)$_2$ aqueous solution for 30 s, rinsed with deionized water and then dipped in 0.5 M Na$_2$S aqueous solution for another 30 s followed by rinsing. This constituted one cycle and the process was repeated four times.

The sensitized TiO$_2$ electrode were then combined with the counter electrode in the presence of polysulfide electrolyte to assemble a typical QDSSC. Photocurrent-voltage (I-V) characteristics of the QDSSCs were measured using a Keithley 2400 electrometer under illumination from xenon lamp at the intensity of 100 $mW/cm^2$.

### 3.4 Determination of optimal SILAR cycles for deposition of PbS and CdS quantum dots

The prepared TiO$_2$ layer electrodes were sensitized using PbS and CdS quantum dots during different cycles. We then integrated these electrodes with the Pt counter electrodes and after injecting the electrolyte into them, we characterized the fabricated cells. Fig. 7 shows the voltage-current density of experimental samples that are sensitized by these two types of quantum dots.
Figure 7: Comparison of the current density-voltage curves of sensitized solar cells with PbS and CdS quantum dots with different SILAR cycles.

Figure 8: As the number of SILAR cycles increases, the color of the electrode changes from pale yellow to orange.

Characteristics of these samples such as efficiency, open circuit voltage and short circuit current density and filling factor were also measured and calculated as shown in the Table 3.

As the number of SILAR cycles in PbS deposition changes, the color of the photoelectrodes changes from pale brown to black. According to the results in the Table 3, the number of optimal cycles in deposition of PbS is 5 and in deposition of CdS is 11 for which the maximum cell efficiency was obtained. With increasing number of SILAR cycles the color of the electrodes changes from pale yellow to orange (see Fig. 8).

The results show that in photoanode sensitized with quantum dots by the SILAR method, as the number of solar cycles increases, the short-circuit current density, open circuit voltage and subsequently the cell efficiency increase until the optimized cycles and then they decrease. When quantum dot deposition is performed with a low number of SILAR cycles, the quantum dots cover the TiO$_2$ layer partially, and an increase in the number of deposition cycles results in complete TiO$_2$ layer coverage. If sensitization is performed over an optimal number of cycles, this increase in the cycle reduces cell
Table 3: Results of current density-voltage characterization

| PbS(X) | CdS(Y) | J<sub>SC</sub>(mA/cm<sup>2</sup>) | V<sub>OC</sub>(V) | η(%) | FF |
|--------|--------|-------------------------------|-----------------|------|----|
| 0      | 3      | 1.13                          | 0.23            | 0.12 | 0.45|
| 3      | 0      | 3.00                          | 0.18            | 0.13 | 0.24|
| 4      | 6      | 3.01                          | 0.39            | 0.59 | 0.51|
| 5      | 6      | 8.44                          | 0.33            | 1.06 | 0.38|
| 6      | 6      | 7.03                          | 0.26            | 0.69 | 0.38|
| 5      | 9      | 11.65                         | 0.31            | 1.26 | 0.35|
| 5      | 10     | 12.81                         | 0.33            | 1.56 | 0.37|
| 5      | 11     | 15.28                         | 0.33            | 1.88 | 0.38|
| 5      | 12     | 14.65                         | 0.31            | 1.42 | 0.32|

performance, which can be attributed to poor charge injection and appears to be due to reduction of quantum effect of larger quantum dots, which reduces the repulsive force for charge injection (electrons and holes) \([21]\), increasing the number of recombinant traps in large quantum dots \([22]\) and prevention of oxidation / reduction ions transfer due to blocking of pores of the structure by quantum dots \([9]\).

3.5 Investigation of the effect of different counter electrodes

Generally, the efficiency of QDSSCs is below 5%. But simulation and theory studies have shown that the efficiency of these cells can reach up to 44% \([7]\). The recombination of carriers at the boundary of the electrolyte quantum dots and the low activity of some of the counter electrodes in the presence of some electrolytes are two major reasons for this low efficiency \([3]\). Gold and platinum are commonly used as counter electrodes and polysulfide electrolytes in QDSSCs. But the conductivity of these electrodes is reduced by the absorption of electrolyte sulfur atoms \([15]\). Therefore, metal sulfides such as CoS are suitable substitutes for Au and Pt, which in addition to having high electrocatalytic activity can transfer holes much better than these materials and improve cell efficiency \([30]\). The Hades Research Group showed that the short-circuit current density is 60 mA/cm<sup>2</sup> and 20 mA/cm<sup>2</sup> in the presence of polysulfide electrolytes for CoS and Pt, respectively \([8]\). We investigated a QDSSC with PbS and CdS sensitizers for the three different electrodes Pt, Au and CoS which current-voltage-density diagram is shown in Fig. \([\]\).

Table 4 shows the results of the characterization of these three cell types. Power conversion efficiency using CoS increased by about 70% compared to Pt and by about 100% compared to Au. By comparing the current-voltage-density diagrams of these three types of cells, it can be seen that the electrodes based on these two metals react strongly with sulfide ions, thereby greatly reduce their catalytic activity and conductivity. However, the CoS electrode is more stable and efficient in the presence of polysulfide electrolyte and its cost is less than other two types.
Figure 9: Current density-Voltage curves for solar cells sensitized with PbS and CdS quantum dots in the presence of Au, Pt and CoS electrodes.

Table 4: Results of current density-voltage characterization of cells made with different counter electrodes

| counterelectrode | $J_{SC}$(mA/cm$^2$) | $V_{OC}$(V) | $\eta$(%) | FF |
|------------------|----------------------|-------------|-----------|----|
| Au               | 7.76                 | 0.38        | 1.03      | 0.34 |
| Pt               | 10.61                | 0.41        | 1.31      | 0.30 |
| CoS              | 12.01                | 0.47        | 2.23      | 0.39 |

3.6 absorption spectrum of Photoanode made by optimized number of SILAR cycles

Fig. 10 shows the absorption spectrum of anode made up of 5 cycles for PbS quantum dots and 11 for CdS quantum dots. The cell absorbs more than 80% throughout the sun’s spectrum. With high absorption of infrared spectra, this anode can have a high carrier production rate.

Using X-ray diffraction characterization of the optimized cell anode, the size of the CdS quantum dots for the optimized cell is approximately 2 nm and the size of the PbS quantum dots was approximately 5 nm. These magnitudes were obtained by using the Debye-Scherrer relation (Eq. 11) [29]:

$$D = \frac{0.94\lambda}{\beta \cos(\theta)}$$  \hspace{1cm} (11)

In this relation $\lambda$ is the wavelength x-ray, $\beta$ is FWHM and $\theta$ is a diffused Bragg’s angle.
4 conclusion

Quantum dot sensitized solar cells with one type of material can achieve more than 12% efficiency using CdSe. Due to its good band-gap for use in solar cells, it can absorb a wide range of visible spectrum. Materials with low energy band-gap such as PbS and PbSe due to their low band gap have high absorption in visible and infrared spectrum of light, but cells made with these materials have a smaller $V_{oc}$ because of more recombination of carriers than other materials. Simultaneous sensitizing using two different materials, one with a large band-gap and the other with a small band-gap, can cause the solar cell absorb more light in the visible, infrared and ultraviolet spectrum. Although at co-sensitized solar cells the $V_{OC}$ decreases, overall the efficiency of this type of cell is higher than sensitized cell with one type of quantum dot. The co-sensitized cell with the PbS and CdS quantum dots has a higher efficiency (Almost 15%) than the other types of co-sensitized cells due to its $J_{SC}$ higher than $20mA/cm^2$ and $V_{OC}$ higher than 0.8V.

Experimental method of fabricating solar cells can greatly influence the characteristics of this cell by changing the number of SILAR cycle. The X-ray diffraction results show that by changing the concentration of precursors, the immersion time and the number of cycles, the size of the quantum dots can be well controlled. A cathode made of CoS, which costs less than platinum and gold cathodes, can increase relative cell efficiency up to 80%. Although the anode made with PbS and CdS quantum dots has high absorption, the efficiency of this cell is low which can be a result of the strongly recombined carriers in these cell.

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