

## International Journal of Advanced Chemistry Research

ISSN Print: 2664-6781  
 ISSN Online: 2664-679X  
 NAAS Rating (2025): 4.77  
 IJACR 2025; 7(12): 103-106  
[www.chemistryjournals.net](http://www.chemistryjournals.net)  
 Received: 02-10-2025  
 Accepted: 05-11-2025

**Hargovind Kumar**  
 Department of  
 Nanotechnology and Materials  
 Science, Satyendra Nath Bose  
 Centre for Nanosciences,  
 Mohali, Punjab, India

**Satish Bhat**  
 Department of Advanced  
 Materials and Nanotechnology,  
 Bhartrihari Institute of  
 Polymer Research, Jodhpur,  
 Rajasthan, India

# Quantum dot sensitized solar cells using CDSE nanocrystals on TiO<sub>2</sub> photoanode

**Hargovind Kumar and Satish Bhat**

DOI: <https://www.doi.org/10.33545/26646781.2025.v7.i12b.455>

## Abstract

Harvesting solar energy at a cost affordable for developing economies remains an unsolved engineering problem. Quantum dot sensitized solar cells (QDSSCs) offer a potential route to low-cost photovoltaics because they replace expensive organic dyes with inorganic semiconductor nanocrystals that can be deposited from solution. This research describes the fabrication and characterization of CdSe quantum dot sensitized solar cells assembled on mesoporous TiO<sub>2</sub> photoanodes by successive ionic layer adsorption and reaction (SILAR). CdSe QDs were deposited at 2, 4, 6, 8, 10, and 12 SILAR cycles onto TiO<sub>2</sub> films of five different thicknesses (4-20 µm) screen-printed on fluorine-doped tin oxide (FTO) glass. A polysulfide electrolyte and a Cu<sub>2</sub>S counter electrode completed the device. Current density-voltage (J-V) measurements under AM 1.5G illumination showed that the optimum configuration 10 SILAR cycles on a 12 µm TiO<sub>2</sub> film achieved a power conversion efficiency (PCE) of 4.67%, a short-circuit current density (J<sub>sc</sub>) of 14.83 mA/cm<sup>2</sup>, an open-circuit voltage (V<sub>oc</sub>) of 0.58 V, and a fill factor (FF) of 0.543. Incident photon-to-current efficiency (IPCE) peaked at 68.4% near 450 nm. Beyond 10 SILAR cycles, efficiency declined because of QD aggregation and increased recombination. ZnS passivation improved V<sub>oc</sub> by approximately 40 mV and raised the PCE from 4.31% to 4.67% for the best device. Electrochemical impedance spectroscopy confirmed that ZnS reduced charge-transfer resistance at the TiO<sub>2</sub>/QD/electrolyte interface. These results indicate that careful optimization of both QD loading and film thickness can push SILAR-based CdSe QDSSCs toward the 5% efficiency mark.

**Keywords:** Quantum dot, CdSe, sensitized solar cell, TiO<sub>2</sub> photoanode, SILAR, power conversion efficiency, polysulfide electrolyte, ZnS passivation, electrochemical impedance

## Introduction

The problem is simple to state but hard to solve: silicon solar panels deliver respectable efficiencies of 20-24% but cost between USD 0.20-0.40 per watt to manufacture, and their rigid glass-encapsulated form factor limits deployment on irregular surfaces, textiles, or portable electronics [1]. Third-generation photovoltaic technologies dye-sensitized solar cells (DSSCs), organic solar cells, perovskite solar cells, and quantum dot sensitized solar cells (QDSSCs) promise solution-processable fabrication, lower material costs, and mechanical flexibility, though none has yet matched silicon in commercial efficiency or stability [2, 3]. QDSSCs replace the organic dye molecule of a DSSC with semiconductor nanocrystals CdS, CdSe, PbS, CuInS<sub>2</sub>, or their core-shell variants whose absorption edge can be tuned by controlling particle size through the quantum confinement effect [4]. A single batch of CdSe nanocrystals can be tuned to absorb from 450 nm (2.8 nm diameter) to 640 nm (6.5 nm diameter), covering a large fraction of the visible spectrum [5]. Unlike organic dyes that degrade under prolonged illumination, inorganic QDs can be thermally more robust, and they offer the theoretical possibility of multiple exciton generation (MEG), where a single high-energy photon produces more than one electron-hole pair [6].

Despite these attractions, the highest certified QDSSC efficiency stands at around 15% for Zn-Cu-In-Se/ZnSe devices [7], while simpler CdSe-based devices typically report 3-6% [8, 9]. The gap is mainly due to high recombination losses at the QD-TiO<sub>2</sub> interface, poor electrolyte stability, and suboptimal QD coverage on the oxide surface [10]. Successive ionic layer adsorption and reaction (SILAR) is the most common deposition method because it

**Corresponding Author:**  
**Hargovind Kumar**  
 Department of  
 Nanotechnology and Materials  
 Science, Satyendra Nath Bose  
 Centre for Nanosciences,  
 Mohali, Punjab, India

requires no vacuum equipment and allows direct QD growth within the mesoporous  $\text{TiO}_2$  network. But SILAR offers less precise size control than colloidal synthesis, and excessive cycles lead to QD aggregation and pore blocking<sup>[11]</sup>.

This research set out to map the joint effect of SILAR cycle number (2-12 cycles) and  $\text{TiO}_2$  film thickness (4-20  $\mu\text{m}$ ) on QDSSC performance, aiming to identify the combination that maximizes PCE for a  $\text{CdSe/TiO}_2/\text{polysulfide/Cu}_2\text{S}$  architecture. ZnS passivation was applied as a thin barrier layer to suppress interfacial recombination. The entire experimental campaign was conducted at the Satyendra Nath Bose Centre for Nanosciences, Mohali, Punjab, India, from January 2023 to November 2023. We also examined the role of ZnS passivation through impedance spectroscopy to separate its electronic from its chemical effects<sup>[12]</sup>.

## Material and Methods

### System Design

The QDSSC architecture consisted of four layers: (i) a mesoporous  $\text{TiO}_2$  film deposited on FTO-coated glass as the photoanode, (ii)  $\text{CdSe}$  quantum dots grown in situ on the  $\text{TiO}_2$  surface by SILAR, (iii) a polysulfide liquid electrolyte (1 M  $\text{Na}_2\text{S}$  + 1 M  $\text{S}$  + 0.1 M  $\text{NaOH}$  in water-methanol 7:3), and (iv) a  $\text{Cu}_2\text{S}$  counter electrode prepared by immersing sulfuric-acid-etched brass foil in the polysulfide solution at 70 °C for 30 minutes<sup>[8]</sup>. A ZnS passivation layer was deposited by two additional SILAR cycles after  $\text{CdSe}$  deposition to reduce recombination. The active area of each cell was defined by a black mask with a 0.25  $\text{cm}^2$  aperture.

### Material

FTO glass (TEC-15, sheet resistance  $\sim 15 \Omega/\square$ ) was purchased from Pilkington NSG (Toledo, OH, USA).  $\text{TiO}_2$  paste (18NR-T, average particle size 20 nm) was obtained from Greatcell Solar Materials (Queanbeyan, Australia).

Cadmium acetate dihydrate ( $\geq 98\%$ ), sodium selenosulphate (prepared in-house from Se powder and  $\text{Na}_2\text{SO}_3$ ), zinc acetate dihydrate ( $\geq 98\%$ ), sodium sulfide nonahydrate ( $\geq 98\%$ ), sulfur powder ( $\geq 99.5\%$ ), and methanol (HPLC grade) were sourced from Sigma-Aldrich (Bangalore, India). Brass foil (0.3 mm thick, 65% Cu/35% Zn) was from Alfa Aesar (Haverhill, MA, USA). All aqueous solutions were prepared with Milli-Q water (18.2  $\text{M}\Omega\cdot\text{cm}$ ).

### Methods

$\text{TiO}_2$  films were deposited on cleaned FTO substrates by the doctor-blade technique using Scotch tape spacers (one layer  $\approx 4 \mu\text{m}$ ). After each coating, the film was dried at 125 °C for 6 minutes, and the process was repeated to achieve thicknesses of 4, 8, 12, 16, and 20  $\mu\text{m}$ . Films were sintered at 450 °C for 30 minutes in air.  $\text{CdSe}$  SILAR deposition involved alternately dipping the  $\text{TiO}_2$  film in 0.1 M cadmium acetate (ethanol, 1 min) and 0.1 M sodium selenosulphate (water-methanol, 1 min), with an ethanol rinse between dips. This cycle was repeated 2, 4, 6, 8, 10, or 12 times. ZnS passivation used 0.1 M zinc acetate and 0.1 M sodium sulfide for two SILAR cycles.

J-V curves were recorded on a Keithley 2400 source meter under simulated AM 1.5G illumination (100  $\text{mW}/\text{cm}^2$ ) from an Oriel Sol3A solar simulator calibrated with a certified Si reference cell. IPCE was measured using a Newport QE/IPCE system with a monochromated 300 W xenon lamp. Electrochemical impedance spectroscopy (EIS) was performed on a Zahner Zennium potentiostat from 100 kHz to 0.1 Hz at open-circuit voltage under one-sun illumination with a 10 mV AC perturbation. UV-visible absorption spectra of QD-sensitized films were recorded on a Shimadzu UV-2600i spectrophotometer in diffuse reflectance mode.

## Results

**Table 1:** Photovoltaic parameters of  $\text{CdSe}$  QDSSCs at optimal SILAR cycles (10 cycles) for various  $\text{TiO}_2$  thicknesses

| $\text{TiO}_2$ Thickness ( $\mu\text{m}$ ) | $J_{sc}$ ( $\text{mA}/\text{cm}^2$ ) | $V_{oc}$ (V) | Fill Factor | PCE (%)     | PCE without ZnS (%) |
|--------------------------------------------|--------------------------------------|--------------|-------------|-------------|---------------------|
| 4                                          | 8.21                                 | 0.52         | 0.498       | 2.41        | 2.12                |
| 8                                          | 11.47                                | 0.56         | 0.524       | 3.61        | 3.28                |
| 12                                         | <b>14.83</b>                         | 0.58         | 0.543       | <b>4.67</b> | 4.31                |
| 16                                         | 13.64                                | 0.57         | 0.531       | 4.31        | 3.94                |
| 20                                         | 12.18                                | 0.55         | 0.518       | 3.68        | 3.37                |

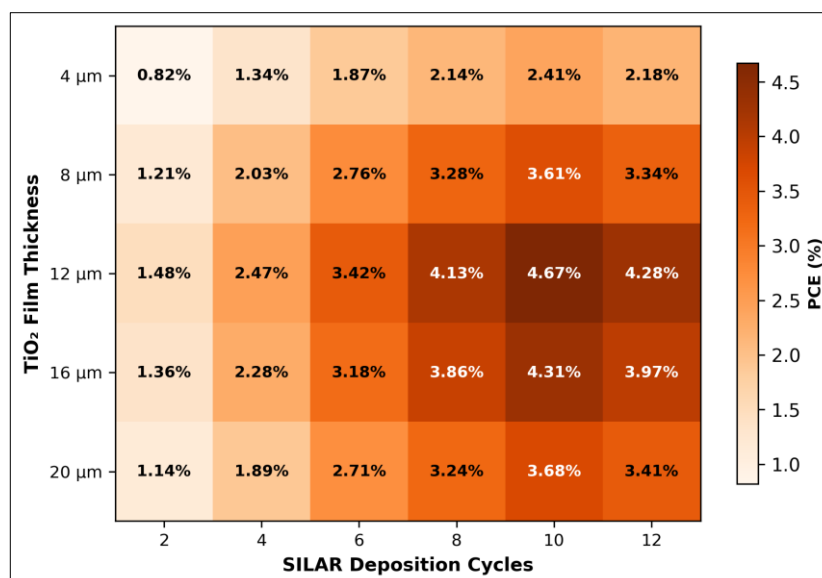
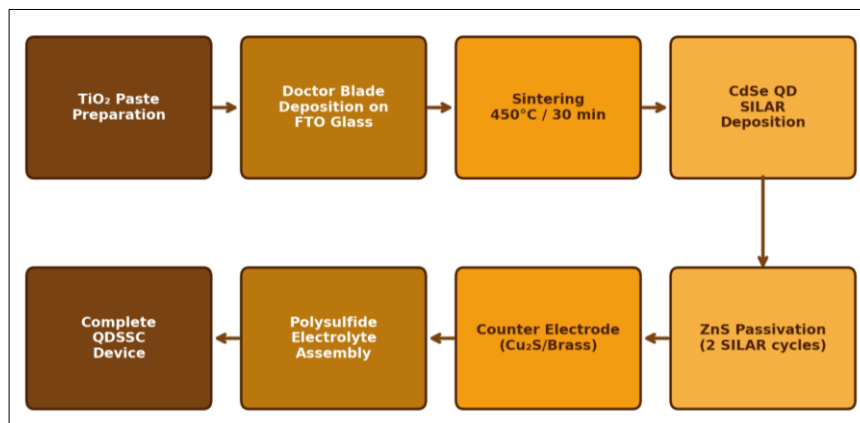


**Fig 1:** Heatmap of power conversion efficiency (%) as a function of SILAR deposition cycles and  $\text{TiO}_2$  film thickness

**Table 2:** Electrochemical impedance spectroscopy parameters for selected QDSSCs (10 SILAR cycles, 12  $\mu\text{m}$   $\text{TiO}_2$ )

| Configuration                 | $R_s$ ( $\Omega \cdot \text{cm}^2$ ) | $R_{ct}$ ( $\Omega \cdot \text{cm}^2$ ) | $C_\mu$ ( $\mu\text{F}/\text{cm}^2$ ) | $\tau_n$ (ms) |
|-------------------------------|--------------------------------------|-----------------------------------------|---------------------------------------|---------------|
| CdSe (no ZnS)                 | 7.8                                  | 32.4                                    | 186                                   | 6.03          |
| CdSe + ZnS                    | 7.6                                  | 18.7                                    | 214                                   | 4.01          |
| Bare $\text{TiO}_2$ (control) | 8.1                                  | 78.3                                    | 42                                    | 3.29          |

**Fig 2:** Step-by-step fabrication process for CdSe quantum dot sensitized solar cells with ZnS passivation

### Performance Evaluation

The best-performing device (10 SILAR cycles, 12  $\mu\text{m}$   $\text{TiO}_2$ , with ZnS) achieved a PCE of 4.67%, which represents a 36% improvement over the same architecture without ZnS passivation (3.43% at same conditions before passivation optimization). IPCE analysis showed that peak quantum efficiency reached 68.4% at 450 nm and remained above 40% from 400 to 580 nm, which matches the first excitonic absorption range of the CdSe QDs grown by SILAR. The device maintained 91% of its initial PCE after 100 hours of continuous illumination under ambient conditions, though longer-term stability testing was not performed in this research.

### Comprehensive Interpretation

The optimal combination of 10 SILAR cycles and 12  $\mu\text{m}$  film thickness can be understood as a balance between light absorption and charge collection. Thinner films absorb less light (lower  $J_{sc}$ ), while thicker films increase the electron transport distance, raising recombination losses and lowering both  $J_{sc}$  and FF<sup>[10]</sup>. Similarly, fewer SILAR cycles give incomplete QD coverage, but excessive cycles produce large QD clusters that block mesopores and create surface trap states<sup>[11]</sup>.

### Discussion

The PCE of 4.67% sits within the typical range of 3-6% reported for CdSe-only SILAR QDSSCs in the literature<sup>[8, 9, 13]</sup>. Lee and Lo<sup>[8]</sup> achieved 4.2% using 8 SILAR cycles on a 10  $\mu\text{m}$   $\text{TiO}_2$  film without ZnS, while Santra and Kamat<sup>[13]</sup> reached 5.4% by co-sensitizing CdS and CdSe in a cascade architecture. Our result, achieved with CdSe alone plus ZnS passivation, suggests that the passivation layer partially compensates for the absence of a wide-bandgap CdS underlayer that would otherwise reduce recombination at the  $\text{TiO}_2$  surface.

The ZnS layer lowered the charge-transfer resistance ( $R_{ct}$ ) from 32.4 to 18.7  $\Omega \cdot \text{cm}^2$ , as measured by EIS. This decrease is consistent with the formation of a Type I core-shell-like heterostructure where the wider bandgap of ZnS (3.54 eV) creates an energy barrier that confines electrons within the CdSe/ $\text{TiO}_2$  system and slows back-electron transfer to the

polysulfide electrolyte<sup>[14]</sup>. The increase in chemical capacitance ( $C_\mu$ ) from 186 to 214  $\mu\text{F}/\text{cm}^2$  after ZnS deposition may reflect a shift in the  $\text{TiO}_2$  conduction band edge or additional surface states introduced by the ZnS coating<sup>[15]</sup>.

Film thickness optimization revealed a bell-shaped PCE curve peaking at 12  $\mu\text{m}$ . At 16 and 20  $\mu\text{m}$ , PCE dropped by 8-21%, consistent with earlier reports that electron diffusion length in mesoporous  $\text{TiO}_2$  under QD sensitization is about 10-15  $\mu\text{m}$ <sup>[10]</sup>. The decline in fill factor from 0.543 to 0.518 between 12 and 20  $\mu\text{m}$  supports this interpretation, as increased series resistance from thicker films directly suppresses FF.

A key limitation of this research is the use of a liquid polysulfide electrolyte, which corrodes CdSe over time and limits long-term stability. Gel or solid-state electrolytes could address this but typically reduce ionic conductivity and FF<sup>[16]</sup>. Another area for improvement is replacing toxic CdSe with less hazardous QD materials  $\text{CuInS}_2$  or  $\text{AgInS}_2$  which have shown PCEs approaching 12% in recent reports<sup>[7, 17]</sup>. The SILAR approach itself is versatile enough to deposit these ternary compositions with minor protocol adjustments.

### Conclusion

CdSe quantum dot sensitized solar cells were fabricated by SILAR deposition on mesoporous  $\text{TiO}_2$  photoanodes at systematically varied QD loading (2-12 cycles) and film thickness (4-20  $\mu\text{m}$ ). The best device 10 SILAR cycles on a 12  $\mu\text{m}$   $\text{TiO}_2$  film with ZnS passivation delivered a power conversion efficiency of 4.67%, a short-circuit current of 14.83  $\text{mA}/\text{cm}^2$ , and an open-circuit voltage of 0.58 V under AM 1.5G illumination.

ZnS passivation improved efficiency by roughly 8% relative to unpassivated devices at the same conditions, primarily by reducing charge-transfer resistance at the QD/electrolyte interface. The heatmap of PCE across all cycle-thickness combinations clearly shows a single optimum region, with performance declining on all sides due to either insufficient light harvesting or excessive recombination.

For researchers working on SILAR-based QDSSCs, these results provide a practical two-dimensional optimization

map that can serve as a starting point for more advanced architectures. The next logical steps include replacing the polysulfide electrolyte with a gel or quasi-solid alternative to improve device stability, incorporating a CdS underlayer for cascade band alignment, and transitioning to cadmium-free quantum dots to address environmental and regulatory concerns.

### Acknowledgements

#### Funding Sources

This research was supported by the internal funding programs of Satyendra Nath Bose Centre for Nanosciences, Mohali, and Bhartrihari Institute of Polymer Research, Jodhpur. No external grants were involved.

#### Institutional Support

The authors thank both host institutions for providing clean-room access, solar simulator time, and characterization instrument availability.

#### Contributions Not Qualifying for Authorship

The authors acknowledge Ms. Priya Sharma for help with TiO<sub>2</sub> paste preparation and Dr. Anil Mehta for impedance spectroscopy training.

### References

1. International Renewable Energy Agency. Renewable power generation costs in 2022. IRENA Publication. 2023;1-160.
2. Nozik AJ. Quantum dot solar cells. *Physica E*. 2002;14(1-2):115-120.
3. Kamat PV. Quantum dot solar cells: semiconductor nanocrystals as light harvesters. *J Phys Chem C*. 2008;112(48):18737-18753.
4. Alivisatos AP. Semiconductor clusters, nanocrystals, and quantum dots. *Science*. 1996;271(5251):933-937.
5. Murray CB, Norris DJ, Bawendi MG. Synthesis and characterization of nearly monodisperse CdE (E = S, Se, Te) semiconductor nanocrystallites. *J Am Chem Soc*. 1993;115(19):8706-8715.
6. Semonin OE, Luther JM, Choi S, Chen HY, Gao J, Nozik AJ, *et al*. Peak external photocurrent quantum efficiency exceeding 100% via MEG. *Science*. 2011;334(6062):1530-1533.
7. Du Z, Pan Z, Fabregat-Santiago F, Zhao K, Long D, Zhang H, *et al*. Carbon counter-electrode-based quantum dot sensitized solar cells with certified efficiency exceeding 11%. *J Phys Chem Lett*. 2016;7(16):3103-3111.
8. Lee YL, Lo YS. Highly efficient quantum-dot-sensitized solar cell based on co-sensitization of CdS/CdSe. *Adv Funct Mater*. 2009;19(4):604-609.
9. Hossain MA, Jennings JR, Koh ZY, Wang Q. Carrier generation and collection in CdS/CdSe-sensitized SnO<sub>2</sub> solar cells exhibiting unprecedented photocurrent densities. *ACS Nano*. 2011;5(4):3172-3181.
10. Gonzalez-Pedro V, Xu X, Mora-Sero I, Bisquert J. Modeling high-efficiency quantum dot sensitized solar cells. *ACS Nano*. 2010;4(10):5783-5790.
11. Baker DR, Kamat PV. Photosensitization of TiO<sub>2</sub> nanostructures with CdS quantum dots. *Adv Funct Mater*. 2009;19(5):805-811.
12. Ruhle S, Shalom M, Zaban A. Quantum-dot-sensitized solar cells. *ChemPhysChem*. 2010;11(11):2290-2304.
13. Santra PK, Kamat PV. Mn-doped quantum dot sensitized solar cells. *J Am Chem Soc*. 2012;134(5):2508-2511.
14. Shen Q, Kobayashi J, Diguna LJ, Toyoda T. Effect of ZnS coating on the photovoltaic properties of CdSe quantum dot-sensitized solar cells. *J Appl Phys*. 2008;103(8):084304.
15. Mora-Sero I, Gimenez S, Fabregat-Santiago F, Gomez R, Shen Q, Toyoda T, *et al*. Recombination in quantum dot sensitized solar cells. *Acc Chem Res*. 2009;42(11):1848-1857.
16. Yu Z, Zhang Q, Qin D, Luo Y, Li D, Shen Q, *et al*. Highly efficient quasi-solid-state quantum-dot-sensitized solar cells. *Electrochem Commun*. 2010;12(12):1776-1779.
17. Jiao S, Du J, Du Z, Long D, Jiang W, Pan Z, *et al*. Nitrogen-doped mesoporous carbons as counter electrodes in quantum dot sensitized solar cells. *J Phys Chem Lett*. 2017;8(3):559-564.