

## Chapter 6

# Solution-processed quantum dot-sensitized solar cell based on “green” materials

Hieng Kiat Jun

*Department of Mechanical and Material Engineering, Lee Kong Chian Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, Sungai Long Campus, Kajang, Malaysia*

## 1 Introduction and current scenario

According to the report released by the World Energy Council, global energy demand will continue to increase from year to year [1]. In fact, the demand for electricity consumption will double beyond the year 2040 [2]. On the other hand, primary energy demand will peak until 2030. This primary energy source includes energy derived from coal, oil, and gas. The slow growth of primary energy is anticipated due to the disruptive trends of emerging energy sources. Coupled with environmental concern, especially on global warming, the adoption of emerging energy sources has begun to encroach into the dominance of the primary energy source. Generally, these emerging energy sources are referred to as alternative energy or green energy, where electricity generation is not derived from fuel and coal. Some examples of such alternative energy sources are solar energy, hydro energy, and wind energy. The provision of energy power will enable the usage of various equipment, be it portable or stationary, to perform useful work, provide valuable output, and sustain the livelihood of humankind. Therefore it is the goal of inventors and researchers to design an efficient energy device where maximum useful energy can be extracted.

As solar energy is abundant, it makes economic sense to harvest solar energy for energy consumption. Not only is it clean and abundant, the conversion of solar energy to electricity does not emit any harmful or toxic gases. The whole energy conversion process only requires a simple solar photovoltaic (PV) or solar cell setup. Thus it is a safe process with no untoward risks. Due to these attractive features, the PV market has been growing at a rapid rate for the past two decades [3]. Furthermore, with in-depth research and increased adoption of

solar PV, various types of PV systems have been introduced. In general, solar cells can be categorized into three generations of technology, namely, first-, second-, and third-generation solar cells (Fig. 1) [4, 5]. First-generation solar cells are silicon-based solar cells such as monocrystalline and polycrystalline solar cells. They are commercially available and were established a few decades ago. Efficiency of the commercial PV of this category solar cell is around 20%, although the possible maximum efficiency is at 33.3% (Shockley-Queisser's limit) [6]. However, because of their complicated processing requirement and high production cost, second- and third-generation solar cells have been gaining popularity due to their low production cost. Second-generation solar cells are thin film solar cells. Due to their thin and lightweight structure, they continue to be developed to match the efficiency of first-generation solar cells. The highest reported efficiency of thin film solar cells has a value exceeding 20% [7]. Some examples of thin film solar cells are gallium arsenic and cadmium telluride solar cells. Third-generation solar cells were introduced as a result of a better understanding of the physical and chemical properties of nanostructured materials. Some examples are dye-sensitized solar cells (DSSCs), quantum dot-sensitized solar cells (QDSSCs), and perovskite solar cells (PSCs). The development of third-generation solar cells has been fast, especially in PSCs where the highest recorded efficiency to date has reached 25%, which matches the performance of silicon-based solar cells but with lower cost [8].

Among the types of third-generation solar cells, QDSSCs have attracted significant attention from solar cell researchers. QDSSCs are a derivative of DSSCs. Instead of a dye, a semiconductor quantum dot (QD) is used as the sensitizer or light converter material [9]. QDSSCs are deemed attractive due to their tunability of light absorption and multiple exciton generation by the semiconductor QD sensitizers. Semiconductor QDs are the core materials for the functionality of QDSSCs, where they harvest sunlight and convert it into electricity via the generation of electron-hole pairs within the internal structure. In most cases, the type of QD materials used are Pb or Cd based such as PbS, CdS, and CdSe. They are mainly used due to better and stable performance. Unfortunately, such materials pose environmental and health risks when they are

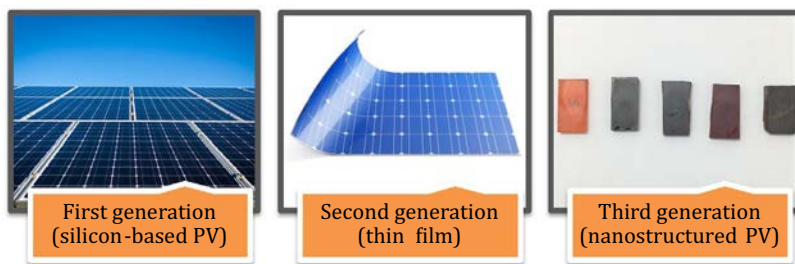


FIG. 1 Classes of solar PV.

exposed or degraded after end-of-life use. Consequently, research has been carried out to analyze the environmental impact of PV devices. The most common analysis carried out is the lifecycle assessment (LCA) of the devices (also known as lifecycle analysis) [10]. Unfortunately, there are not many reports of LCA on QDSSCs. The nearest comparison is on DSSCs and QDPVs [11].

Exposure to heavy metals like Cd and Se has been linked to cancer and degenerative diseases as well as environmentally potential damaging factors [12, 13]. The remedy for this problem is to use “green” materials [14]. The term “green” materials refers to the absence of harmful and toxic heavy metal elements such as mercury (Hg), antimony (Sb), arsenic (As), lead (Pb), cadmium (Cd), and chromium (Cr). In some cases, cobalt (Co) is also included in the heavy metal list. For fully “green” QDSSCs, the entire solar cell structure should not have any of the heavy metal elements mentioned. This applies to the architecture of anode, cathode, and electrolyte (or redox mediator). Thus researchers are left with a few options, which are discussed in Section 3. Before any attempt to upscale QDSSCs, one should understand the fundamental principles and working mechanism behind this PV. Next, a suitable fabrication technique should be reviewed and explored. Finally, challenges and limitations of “green” QDSSCs should be reviewed for future research plans. It is not the intention of this chapter to give a comprehensive and exhaustive review, but rather to provide insight based on notable findings in this niche area.

## 2 Fundamental principles of QDSSCs

Over the past decade, QDSSCs have seen much improvement particularly in power conversion efficiency. The first few reported QDSSCs had an efficiency of less than 1%. A recent result showed that it has reached 16%, which is quite a good development within a short period of time [15]. The rapid development of QDSSCs is attributed to the simple structure and facile fabrication method. QDSSCs take root in DSSCs where both have similar architecture, that is, a sensitized photoanode attached to a cathode electrode (counter electrode) with electrolyte (redox mediator) in between them (refer Fig. 2).

In the anode electrode, nanoparticles of a wide bandgap semiconductor like  $\text{TiO}_2$  are layered on the surface of the conducting substrate. Semiconductor QDs are then attached to the layer of  $\text{TiO}_2$ . This is where the sensitizing effect takes place. Typically, the particle size of  $\text{TiO}_2$  is larger than the size of individual QDs (refer to the inset in Fig. 2). Meanwhile, on the cathode electrode, a layer of catalytic noble metal like platinum or gold is deposited on the conducting substrate surface. The electrolyte consists of a redox couple such as polysulfide electrolyte. It should be noted that polysulfide electrolyte has been proven to be compatible with QDSSCs, particularly Cd-based QDSSCs due to lower charge recombination [9, 16].

In terms of working mechanism, both DSSCs and QDSSCs share a similar mechanism except that semiconductor QDs are involved in QDSSCs instead of

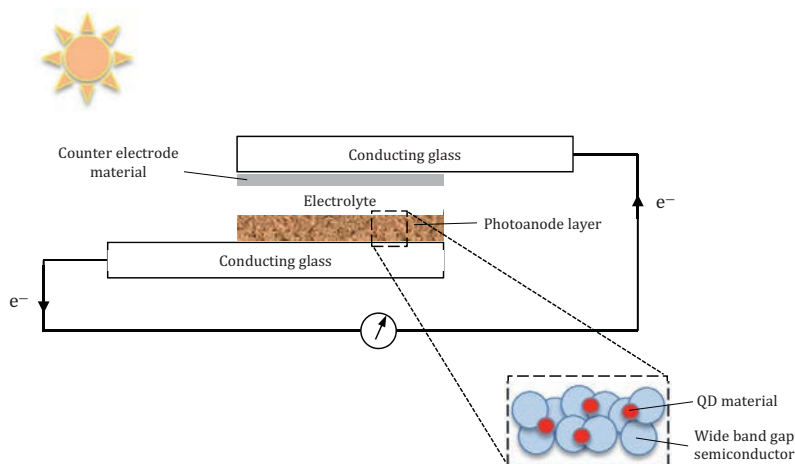


FIG. 2 Schematic of a QDSSC.

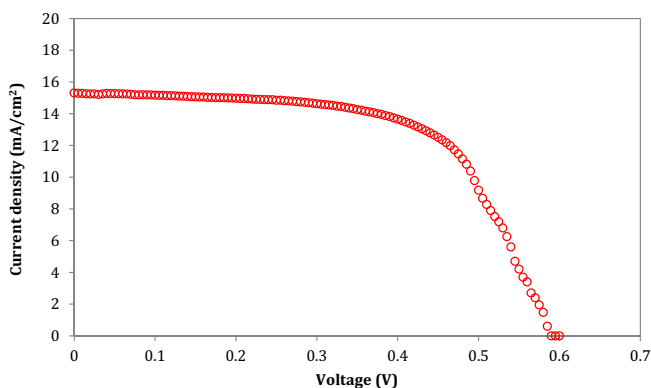
dye molecules [17]. When the device is exposed to light, the electrons within QDs will be energized. This will allow the electron to move from the valence band to the conduction band of the QD. However, such action will only be possible if the light spectrum matches the activation stage of the QD since different QD sizes correspond to different wavelengths of light absorbance. As the activated electron moves to the conduction band, an electron-hole pair is created. Electrons will then be injected into the  $\text{TiO}_2$  layer and proceed to the external circuit to perform work. At the same time, the hole will oxidize the polysulfide electrolyte to recover the stable state of the QD. At this juncture, the electron that has completed the work will reach the counter electrode where it will be used to reduce the oxidized polysulfide electrolyte. The whole cycle will be repeated as long as there is light and a closed loop external circuit.

The performance of a QDSSC is a measure of percentage of useful work obtained from the conversion of light to electricity. The parameters can be obtained from the plot of current density ( $J$ ) against voltage ( $V$ ). Fig. 3 shows the generic  $J$ - $V$  plot with its main parameters.

In essence, the important parameters that govern the performance of QDSSCs are short-circuit current density ( $J_{\text{SC}}$ ), open-circuit photovoltage ( $V_{\text{OC}}$ ), fill factor (FF), and efficiency. Efficiency is also expressed as power conversion efficiency (PCE) and is calculated as follows:

$$\text{PCE}, \eta(\%) = \frac{J_{\text{SC}} \times V_{\text{OC}} \times \text{FF}}{P} \times 100$$

where  $P$  is the incident solar power applied on the device. This equation depends on the light conversion efficiency and electron-hole pair formation and injection. It also depends on the electron lifetime [18]. For a representative



**FIG. 3** Generic plot of current density ( $J$ ) versus voltage ( $V$ ).

and trustworthy result, the measurement of  $J$ - $V$  response should be conducted in a standard manner [19].

To further understand the performance of QDSSCs, electrochemical impedance spectroscopy (EIS) is usually conducted [19, 20]. The EIS result can provide insight into the kinetics of charge collection, transport, and recombination from a single measurement. The notable response used for interpretation is the Nyquist plot. In this plot, a well-defined QDSSC configuration will yield two semicircles that are the manifestation of responses at high and middle-to-low frequency. Series resistance ( $R_s$ ), charge-transfer resistance ( $R_{ct}$ ), and recombination resistance ( $R_{rec}$ ) can be derived from the plot.

Besides the aforementioned characterization methods, other notable approaches include time-resolved photoluminescence, ultrafast transient absorption, open-circuit voltage decay, and charge-extraction measurements.

### 3 Alternative materials for active layers in QDSSCs

As discussed, a typical QDSSC consists of two electrodes coupled together with an electrolyte intermediated between the two electrodes. The photoanode electrode is formed with a nanostructured layer. The usual material for the nanostructured layer is  $\text{TiO}_2$ , a wide bandgap semiconductor. Such a combination is called a  $\text{TiO}_2$ -based photoanode. The earlier design had the  $\text{TiO}_2$  layer sensitized with dyes, or in other words, attached with dye molecules. To boost the performance of the QDSSC, three-dimensional hierarchically branched  $\text{TiO}_2$  nanowires are presented. Such cells can produce higher PCE. The improved performance of these cells is attributed to the increased QD attachment sites where the nanowires consist of long nanowire trunks with short nanorod branches. Besides  $\text{TiO}_2$ ,  $\text{ZnO}$ -based photoanodes have also been tested. Although  $\text{ZnO}$  as the wide bandgap material for QDSSCs is limited by its lower stability compared with  $\text{TiO}_2$ , it is relatively easy to crystallize with anisotropic

crystal growth. When the ZnS surface is treated with  $\text{TiO}_2$ , a decrease in charge recombination at the interface is postulated.

Due to the possible adverse afterlife effect of Cd- and Pb-based QDSSCs, alternative “green” QD sensitizers should be explored as substitutes [14, 21]. The commonly explored “green” QD sensitizers are free of toxic Cd and Pb elements. In some research, other elements like Se, Sb, and Co are also excluded in the “green” QDSSC architecture. Some examples are  $\text{Ag}_2\text{S}$ , SnS,  $\text{Bi}_2\text{S}_3$ , and  $\text{CuInS}_2$  [22–25]. Among these options, ternary and quaternary Cu-based compounds have proven to produce better efficiency. An Ag-based QD is deemed to be the best candidate “green” material. Unfortunately, the compound does not produce sufficient efficiency for further upscaling.

Tubtimtae et al. started the investigation on Ag-based QDSSCs by sensitizing  $\text{TiO}_2$  film with  $\text{Ag}_2\text{S}$  QDs [22]. Their approach was the investigation of the effect of different successive ionic layer adsorption and reaction (SILAR) cycles to the efficiency of  $\text{Ag}_2\text{S}$  QDSSCs. The best result was obtained in samples prepared from four dipping cycles with ZnS as the QD coating layer. Such a device produced an efficiency of 0.98% with a  $J_{sc}$  of  $7.3 \text{ mA/cm}^2$ . The group then tried another Ag-based QDSSC, that is,  $\text{Ag}_2\text{Se}$ , which produced better performance than the  $\text{Ag}_2\text{S}$  QDSSC [26]. Their best solar devices yielded a power conversion efficiency of 1.76% under approximately 1 sun.

Bi-based QDs also have the potential to be the substitute sensitizer for QDSSCs. Desale et al. reported their attempt to improve the photosensitivity of  $\text{Bi}_2\text{S}_3$  synthesized from the SILAR process [24]. When the  $\text{Bi}_2\text{S}_3$  thin film was annealed at  $250^\circ\text{C}$ , the bandgap energy decreased, coupled with improved photoresponse. Unfortunately, the performance of  $\text{Bi}_2\text{S}_3$  QDSSCs remained relatively low compared to Cd-based QDSSCs. One of the reasons for low performance is attributed to the formation of  $\text{NaBiS}_2$  instead of  $\text{Bi}_2\text{S}_3$  during the SILAR process [27]. The remedy for this problem is to replace  $\text{Na}_2\text{S}$  solution (precursor for S) with elemental S vapor. The QD synthesized from vapor method has resulted in a better performance at 0.84%, although this value is still low. Cosensitization of the  $\text{Bi}_2\text{S}_3$  QD with the CdS QD could further improve the power conversion efficiency of the QDSSC [28]. Unfortunately, such QD architecture has defeated the purpose of achieving “green” and sustainable solar cell devices. A better option would be the ternary compound  $\text{AgBiS}_2$  [29]. To produce ternary  $\text{AgBiS}_2$  QDs, a two-stage SILAR process was introduced. The produced cell exhibited a  $J_{sc}$  of  $7.61 \text{ mA/cm}^2$  and efficiency of 0.53%. With such a low efficiency, perhaps the best approach is to redesign the solar cell architecture. Bernechea et al. produced a solution-processed  $\text{AgBiS}_2$  solar cell with power conversion efficiency of 6.3% [30]. Such cell had the architecture of  $\text{ITO/ZnO/AgBiS}_2/\text{polymer/MoO}_3$ .

Probably the most widely studied “green” QD material is SnS. Tsukigase et al. demonstrated the feasibility of fabricating SnS nanoparticles for application in solar cells [31, 32]. Although SnS QDs are easy to synthesize (the simplest approach is a solution process with precursors of Sn and S ions), their

performance as a solar energy converter agent still needs much improvement. A thorough study of the compatibility of SnS with other counter electrode and electrolyte materials is very much needed. In one of the reported studies, Guo et al. fabricated an SnS QDSSC with TiC as its counter electrode and organic disulfide/thiolate electrolyte system [33]. An efficiency of 1.03% was reported in that study. This result showed that QDSSCs can function in a redox couple system, which is beyond the usual polysulfide system. Its stable performance is attributed to the catalytic selectivity of TiC counter electrode for a disulfide/thiolate electrolyte system. A systematic study of the solution-processed parameters of SnS QDs has been performed by Deepa and Nagasaki [34]. In their work, SnS QDs were fabricated via the SILAR process. The optimum dipping cycle was determined. The best cell performance was reported at 0.54% with Cu<sub>2</sub>S as the counter electrode and polysulfide electrolyte system. Hortikar et al. also did a similar optimization study on SnS QDSSCs [35]. Nevertheless, the performance is still on the low side. This raises a question: Are “green” QDs like SnS suitable for use as a light-to-electricity converter? Perhaps such material performs well in other parts of the active layer of the QDSSC such as the counter electrode. Dai et al. showed that SnS thin film can function as a counter electrode [36]. In addition, the application of noble metals like Pt and Au as cathode electrodes might not be suitable for QDSSCs where a polysulfide electrolyte is used. In such a case, metal chalcogenides and polymer-based materials like Cu<sub>2</sub>S and poly(3,4-ethylenedioxythiophene) have proven to be effective counter electrode materials [37]. The efficacy of such counter electrode materials is attributed to their good electrocatalytic activity as well as compatibility with the electrolyte system. Other attempts to produce interesting and value-added QDSSCs include solid-state “green” QDSSCs, although the performance is far from feasible [38]. On the other hand, a comparable performance of solid-state Cd-based QDSSCs has been proven by using gel-type electrolyte instead of the usual solid-state spiro-ometad [39]. A notable list of “green” QDSSCs is given in Table 1. It must be noted that the list of “green” QDSSCs is confined to QD elements that meet the criteria of “green” material as defined in an earlier section.

## 4 Fabrication of “green” QDs and QDSSCs

A typical QDSSC can be fabricated with various techniques, namely, chemical bath deposition (CBD), SILAR, microwave-assisted CBD, molecular linker attachment, direct adsorption, and electrophoresis. Among these techniques, solution-processed techniques like CBD and SILAR are more frequently used due to their ease of processing method and low cost [45]. In both techniques, photoanode samples usually consist of conducting glass coated with wide band-gap semiconductor particles such as TiO<sub>2</sub> and ZnO.

The CBD fabrication technique was adopted a long time ago, particularly in depositing CdS layers for thin film-based PV devices. This method is also

**TABLE 1** Performance of some “green” quantum dot-sensitized solar cells.

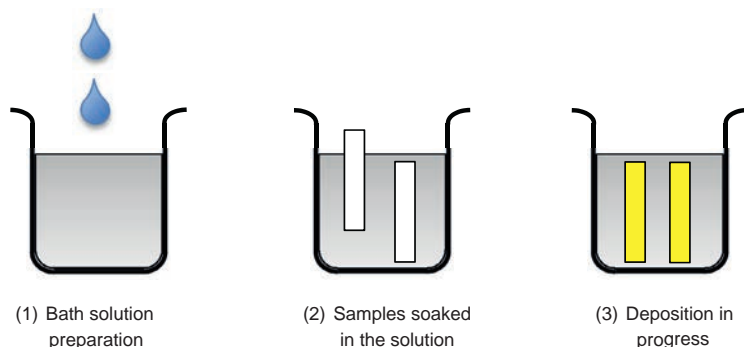
“Green” QDs	$J_{SC}$ (mA/cm <sup>2</sup> )	$V_{OC}$ (V)	PCE (%)	References
Ag <sub>2</sub> S	9.28	0.509	2.41	[40]
InP	10.58	0.590	3.54	[41]
CuInS <sub>2</sub>	22.82	0.601	8.54	[42]
Zn-Cu-In-S	22.70	0.612	8.55	[43]
Cu <sub>2</sub> ZnSnS <sub>4</sub>	17.48	0.47	3.29	[44]

*PCE*, Power conversion efficiency; *QDs*, quantum dots.

applied in other electronic devices such as sensors, conductive oxide coatings, and catalyst deposition. The widespread adoption of CBD in solar cell devices occurred around 1990 [46]. At the laboratory scale, CBD is performed in a beaker with a metal salts solution. A saturated solution is preferred for ease of nucleation of the QDs. In some cases, complexing agents and buffer solutions may be included. Fig. 4 shows a schematic diagram of a typical CBD process. This technique provides the flexibility for obtaining different sizes of nanostructure particles. The formation of QDs via CBD is preceded with the nucleation of nanostructure seeds. This is followed by particle growth. Liu et al. reported the deposition of CdSe QDs on TiO<sub>2</sub> film with proven photoelectrochemical performance [47]. Lokhande et al. also reported several findings with the CBD technique [48, 49]. For “green” QDs, Deepa et al. showed that SnS QDs can be fabricated with this simple technique as well [23]. In their work, SnS QDs were prepared from a solution of SnCl<sub>2</sub> and thioacetamide with deposition time ranging from 30 to 120 min. The produced QD sizes had a range between 2.6 and 15.5 nm. The longer the deposition time, the bigger the QD size obtained. On the downside, performance of the samples obtained from this work was low. The best efficiency obtained was 0.11%. A study by Adhyapak et al. also showed the fabrication of SnS QDs with the CBD technique [35]. They prepared nanoparticles by ultrasound-assisted CBD, where the bath solution consisted of SnCl<sub>2</sub> with ethanolamine as the capping agent. In addition, ammonia and trisodium citrate solutions were used as buffer and complexing solutions, respectively. Similar to previous work, a low performance value was recorded, where the current density was 60 μA/cm<sup>2</sup>, the open-circuit voltage was 135 mV, and the fill factor was 18%.

Due to the low performance of samples prepared from the CBD method, an improved solution technique was introduced by Nicolau in 1985 [50]. Since then, the SILAR technique has been widely used for the synthesis of QD nanoparticles. In this technique, the growth of QD nanoparticles depends on ion-by-ion reaction and growth, which involves the adsorption and reaction of cations



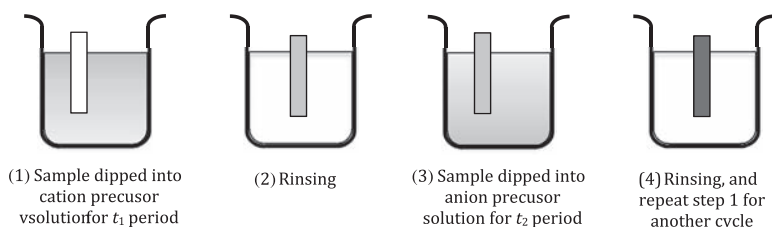


**FIG. 4** Schematic of CBD.

and anions from two separate solutions. This is possible when cation precursor solution and anion precursor solution are prepared separately. Samples are then dipped into ionic precursor solutions successively, with rinsing during the interval dipping process. This dipping process is deemed to be one cycle. The dipping process is usually repeated, depending on the number of cycles required for the sample. The control parameters involved here are dipping time, reaction temperature, precursor solution concentration, and number of dipping cycles. Fig. 5 depicts the schematic process of a typical SILAR method. The fabrication of “green” QDs has been demonstrated by a few groups. Notable facile syntheses of QDs are  $\text{Ag}_2\text{S}$  and  $\text{Bi}_2\text{S}_3$  [22, 27, 51]. Last but not least, hot injection has become an important method of synthesizing high-performing QDs. Unfortunately, this method is seldom reported in the fabrication of “green” QDs. Perhaps a new approach is needed in designing the synthesis route. For more details on the hot-injection method, readers are recommended to refer to the chapter titled “Colloidal Quantum Dot-Based Solar Cells” within this book.

## 5 Challenges and limitations

The major challenge for achieving good performance with QDSSCs is minimizing the charge recombination. Due to the different properties and behaviors of each component in the QDSSC, charge recombination is an avoidable



**FIG. 5** Schematic of SILAR.

phenomenon. It can occur in a few paths such as between the interface of a wide bandgap semiconductor and QD sensitizer, between the QD sensitizer and the electrolyte, and between the wide bandgap semiconductor and the electrolyte. It can also occur within the QD sensitizer itself where the energized electrons at the conduction band recombine with the hole, which ultimately reduces the number of available free electrons. Besides, for QDSSCs where there is a linker agent between the QDs and the wide bandgap semiconductor, recombination exists within the linkage, which is known as intraparticle recombination [52]. There are two main approaches to minimizing the charge recombination in QDSSCs. These strategies include materials engineering and surface treatment.

To reduce the charge recombination within the photoanode interface layer, treatment of the surface with a passivation layer is the most widely used technique. In such a strategy, ZnS has been employed in QDSSCs as a passivation layer. Such a technique has yielded an efficiency improvement of 10% or more [53, 54]. The improved performance is due to the passivation effect of the ZnS layer. The layer is responsible for hindering the back-electron transfer across the interface. It also increases the rate of electron transfer. For a ZnO-based photoanode, passivation of the surface with TiO<sub>2</sub> proved to be effective in reducing interfacial charge recombination as well [55]. Other metal oxides like MgO and Al<sub>2</sub>O<sub>3</sub> have also been used to act as a passivation layer. It should be noted that the application of a passivation layer could only help in improving the performance of QDSSCs to a certain extent.

In recent years, performance improvement in QDSSCs as seen in Cd-based and Se-based QDs has been quite encouraging [5, 9, 14]. Such improvements were attributed to the enhancement in heterointerface engineering and bandgap alignment of QDs. Although the solution process has yielded a high coverage of QDs on the wide bandgap semiconductor surface, the nanoparticle growth process has created numerous trap-state defect sites in the QD layer. The consequence of this phenomenon gives rise to weak optoelectronic properties. As such, a high-performing “green” QD should be the main focus for future study. Unfortunately, the material engineering approach for “green” QDs is the most challenging task since not many “green” material compounds can serve as high-performing QDs. Nevertheless, with proper understanding of the properties and structure of the compounds, we may see better performance from QDSSCs utilizing “green” elements, such as CuInS<sub>2</sub> and Zn-Cu-In-Se, in the near future.

Another alternative is fabrication of the core-shell structure. Unfortunately, there are not many reports of QD core-shell structures based on “green” elements. This could be attributed to the nonsynergistic bandgap alignment among the “green” elements. The commonly reported QDs for such structures consist of CdS- or CdSe-based compounds. Probably the only notable report is by Zhong et al. [25]. In their work, core-shell CuInS<sub>2</sub>/ZnS QDSSCs produced an efficiency of 7.04%. As such, perhaps the best approach to date is the fabrication of ternary and quaternary QD compounds. Some examples are CuInS<sub>2</sub>, Cu<sub>2</sub>ZnSnS<sub>4</sub>, and Zn-Cu-In-S (refer to Table 1). The improved performance

delivered by the QD compounds could be attributed to the fast injection of charge as well as lower charge recombination rate within the structure. On the other hand, some researchers suggested that preprepared QDs could provide a better way to control the charge recombination issue [56]. The preprepared QDs are normally synthesized via the solution process as well. The best recorded QDSSC performance was achieved by Pan et al. through dual sensitizers of Zn-Cu-In-Se and Zn-Cu-In-S, although the presence of an Se element could be a concern for toxicity risk [57]. The strategy of cosensitization of two groups of QD sensitizers has yielded improved performance, which was attributed to better light-harvesting capability, fast electron injection, and reduced charge recombination rate. Unfortunately, QDSSCs with pure “green” compounds using the cosensitization technique have not been reported anywhere. The presence of an Se element seems to play an important role in the performance of a QD sensitizer.

## 6 The way forward

As conventional QDSSCs use Cd- and Pb-based materials as sensitizers, the impact of these substances on the toxicity effect to the environment and human health has become a major concern. Although “green” QDs may pose minimal environmental and health risk effects, the amount of waste that will be produced should be monitored and managed as well. One of the proposals is the implementation of end-of-life management policies [58]. Such policies should be translated into concrete actions or procedures. These include setting up a management body to collect and segregate the unused or expired PV devices for proper disposition. Nevertheless, the most effective approach will be the total elimination of Cd- and Pb-based compounds as materials for QDSSCs. To achieve this, effective “green” QD sensitizers are needed. Thus continuous investigation and research in this area are necessary. Based on the previous work by various groups, research into “green” QDSSCs has been observed to gain traction. As the highest reported performance QDSSC consists of quaternary QD compounds, we may expect that the future trend of QDSSCs will move toward the study of complex compounds. It is expected that the ratio of Cd in compounds will be reduced too. To some extent, Cd-free compounds with high efficiency could be possible. Additionally, the other major factor that needs to be considered is the fabrication technique of “green” QDSSCs. This forms part of the overall LCA of the QDSSC itself. No doubt the current effective fabrication technique will be a solution-based process, combining a number of methods, such as microwave-assisted CBD [59]. Most importantly, the processing technique should be “green,” which means no elements of Cd or Pb are involved throughout the fabrication steps. Since “green” QDs are prepared from their respective precursors, it is very unlikely that Cd- or Pb-based chemicals will be used unless they are needed as a catalyst or precursor for the intermediate process. Therefore based on these observations, adoption and upscaling of

“green” QDSSCs are possible. Researchers should take heed of the call to introduce sustainable and environmentally friendly materials and processes. Finally, governments should encourage participation and research in this field, which have been very encouraging over the last decade.

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