The Use of Quantum Dots for Solar Energy Conversion: A Brief Review

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Abstract
One of the more rapidly growing fields in science today is solar energy conversion. An emerging technology in this field is the use of so called “Quantum Dots”, semiconductors which are small enough to have discrete energy levels. In this literature review, some of the basic photochemistry and photophysics of solar energy generation will be established. A series of articles will then be reviewed, painting a picture of how quantum dots can convert the energy found in photons to useful electricity.

Keywords
Photochemistry — Quantum Dots — Solar Cells — Reviews

1. Introduction

1.1 Background
Canada, a country with a relatively small population, used nearly 9 exajoules (10^{18}) of energy in 2012 and this value has increased by over 12% since 1990 [1]. While demand is increasing, fossil fuels, the most widely used energy source of the 20th century are running out, and reserves may be depleted in the next 100 years [2]. These fuels also contribute to climate change, a phenomenon which could have devastating effects on the future of the Earth [3]. Thus to maintain current consumption levels, an alternative source of energy is required.

There are numerous candidates for such an energy source, a promising example being the Sun, which provided energy to the fossils that give fossil fuels their name. The Sun provides, depending on location, on the order of 100s of watts per square meter of the Earth’s surface (after loss to the atmosphere) [4]. This translates to many orders of magnitude more solar energy being available at Earth’s surface than is used in human activities in any given time period.

1.2 Photovoltaics
With the sun as a source of energy, the next step is to harness its energy. This is where solar cells come in. Most methods of solar energy collection and converting it into electricity involve photovoltaic cells, with a few exceptions that operate thermally [5]. Although this review will look at quantum dot (QD) solar cells, all photovoltaic cells work on a relatively simple basic principle, and the explanation of quantum dots is best made if extended from the common theory of bulk-semiconductor-based photovoltaic cells.

In a semiconductor, there is a conduction band and a non-conducting valence band that are separated by a potential energy called the band gap, $E_g$ [6]. The potential energy of the electrons in this system is known as the Fermi level, and falls between the conducting and valence bands [6]. If enough energy is added to the electrons in the band gap (in this case through light) they can be promoted to the conducting band, leaving behind a positively-charged “hole” in the valence band [6]. This coexistence of hole and electron is known as an exciton pair (see Figure 1) [7].

![Figure 1. From [6], schematic of the generation of an exciton pair by promotion of an electron from the valence band to the conducting band.](image)

This principle is useful, however, for the functioning of a photovoltaic cell, there needs to be another important consideration. If only one material was used, the excited electron would find its way back to the hole and no net current would be generated. To solve this issue, photovoltaic cells contain multiple variations of the semiconductor being used. N-type semiconductors have been modified by adding electron rich atoms to have extra free floating electrons. This leaves fixed extra positive charges in the material and a raised Fermi level. P-type semiconductors are the opposite, with fewer electrons than the normal semiconductor atom/molecule, and therefore positive electron holes that can be thought of as moving around resulting in a lower Fermi Level [6].

If a junction is created between the levels, the average
potential of the electrons in the system must be the same which means a constant Fermi level. However, the distance between the Fermi Level and the bands in both the P-type and N-type also remains constant. This means that the P-type bands must have a higher energy than N-type bands. When electrons in the junction are excited by light, they only flow in one direction down the potential energy surface towards the N-type semiconductor. If this system is attached to a circuit a current can be generated (see Figure 2).

![Figure 2](image)

**Figure 2.** From [6], potential energy surface created by the combination of a P-type and N-type semiconductor. A potential difference is created which means when electrons are excited, they flow to the N-type semiconductor.

This is the system used in most commercial solar cells and works quite effectively. However, there are a few key limitations which mean modifications are worth exploring. First, as calculated by Shockley and Queisser over 50 years ago, single junction solar cells can only be around 30% efficient [8]. This is due to a number of reasons. The first is that any incident light with less energy than the band gap will not contribute in any way to the current. Another problem is that with photons of an energy much greater than the band gap, only a single electron will enter the circuit and much of the energy is wasted thermally [7]. Even using multiple junctions with varying band gaps the maximum efficiency is not ideal. QD solar cells can help to minimize some of these problems to maximize solar energy conversion efficiency.

### 1.3 Basics of Quantum Dots

QD solar cells work on similar principles to bulk semiconductors, but with a few key differences. The first is the difference in the nature of the conduction band that gives quantum dot solar cells their name [7]. Instead of the broad continuum bands seen in bulk semiconductors, the absorbing structures in QDs are small enough (a few nm across) that they act like atoms with discrete (quantized) energy levels [7]. The quantization arises from a property of excitations known as the Exciton Bohr Radius, which is a measure of the initial separation of the electron and hole [9]. In bulk semiconductors the crystal structure is much larger the Bohr Radius, however, quantum dots are semiconductor crystals similar in size to the Bohr Radius which results in confinement and thus quantization (see Figure 3) [10].

![Figure 3](image)

**Figure 3.** From [11], demonstration of the quantization that occurs in QD solar cells. Smaller quantum dots tend to result in larger bandgaps.

The difficulty comes in exploiting this property to produce useful energy, as there still must be electrons flowing through a circuit or a chemical system to create work. The focus of this review will be how the various properties of quantum dots can be used to turn the Sun’s energy into useable energy. Since there are numerous approaches, this review will only focus on portions of a few interesting papers in this newly developing field.

## 2. Tuning photoresponse

**Quantum dot solar cells. Tuning photoresponse through size and shape control of CdSe – TiO$_2$ architecture**

**Konkanand et al**

### 2.1 Introduction and motivation

One problem with bulk semiconductors is they are often quite limited in the portion of the solar spectrum that they can use [12]. Since, the sun is a broad spectrum light source much of its energy goes to waste (See Figure 4).

![Figure 4](image)

**What would be useful in this case is having a solar cell that can adapt to a variety of different wavelengths of sunlight. The first paper from Konkanand’s group included in this review looked into how QD solar cells can be adapted using the shape and size of the CdSe – TiO$_2$ structure to control photochemical properties [10]. This paper also included some substrate considerations and is a good overview of the field in general.**

In most cells that use QDs, they are used as sensitizers, which means that they absorb photons and then transfer the excited electrons to a semiconductor that would have too large a bandgap to be useful in the visible region under normal circumstances. These substrate semiconductors themselves are small particles connected together submerged in an electrolyte so that the same process of electrons moving through the system that occurs in traditional semiconductors can occur.
Figure 4. From [13], Air mass 1.0 demonstrates the wide spectra distribution of the light incident on the Earth’s surface when the incident solar rays are normal to the Earth’s Surface. Higher air masses occur when solar rays the atmosphere at an angle. Note that this spectrum varies depending on location and weather.

Figure 5 demonstrates the general function of a dye-sensitized solar cell, (QDs act as a dye).

Figure 5. From [6], sample schematic of a dye sensitized solar cell, QDs replace the dye in this schematic. Specific devices vary significantly from this sample device.

This transfer process was not, however, the focus of the paper; instead, the study looked into changing the nature of the CdSe nanoparticles to see what effect they had on various solar cell properties. What is interesting about this modification is that the changing of the QDs themselves is a fairly simple process.

2.2 Experimental

The methodology for preparing the CdSe QDs is a simple wet chemistry experiment that could be done in many undergraduate level labs. First, cadmium reagents are added to a flask which is heated in a nitrogen atmosphere to around 300°C. After cooling slightly using addition of the selenium reagent, the solution is heated at a constant temperature with monitoring under UV-visible spectroscopy until the particles grow to the required size. The spectroscopy uses the fact that smaller particles absorb at a lower wavelength (due to increased confinement) to identify the size of particles.

The more complicated step in preparation comes in the deposition of the nanoparticles onto the TiO$_2$ and creating the structure required to transport the electrons. To form the TiO$_2$ structures used in this experiment, a few more advanced, yet still accessible, techniques were used. To form the traditional particulate based cells, powdered TiO$_2$ was added to gelling agents and then deposited on a glass electrode using the doctor-blade technique. This technique involved rolling the TiO$_2$ coated glass underneath a fine blade to achieve a uniform thin layer of TiO$_2$. The method to form the nanotube structure involved using a mesh counter electrode and certain electrolytes that result in a nanotube array being formed upon applied voltage.

In each case the TiO$_2$ structures were then annealed to the transparent glass electrode using high temperatures. To add the quantum dots, a few reagents were added to ensure that the CdSe dots annealed and then the electrodes were simply dipped into a CdSe solution with the correctly sized particles and left to sit for a few days.

After the cells were prepared, xenon arc lamps with monochrometers were used to provide light for the cell at various wavelength. Spectrophotometers and spectrofluorometers could be used to determine optical properties and high sensitivity ammeters and voltmeters were used to measure electrical properties. This type of setup is quite common for solar cell experiments.

2.3 Results

The first fact that needs to be established is that the transfer of electrons from the quantum dots to the TiO$_2$ structure is indeed occurring. This paper determined this was the case by comparing the fluorescence of the free CdSe quantum dots to those deposited on the TiO$_2$ structure. The quantum dots deposited on the TiO$_2$ had significantly decreased fluorescence which indicates that most electrons are likely transferred to the TiO$_2$ rather than relaxing in the CdSe (see Figure 6).

Next, it is important to know that the change in the size of the quantum dots has a clear effect on the part of the spectra that the quantum dots absorb. This has been demonstrated in previous papers and was again demonstrated here. The novelty in the paper comes from determining with more detail what these different sizes and absorptions mean for power conversion efficiency at various wavelengths. Firstly, this paper demonstrates that these differences in quantum dot absorbance carry over to the differences in absorbance of the cell itself. This may seem obvious, however, it is important to ensure that changes in QDs carry over to the cell itself (see Figure 7).
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Another important finding is that the varying sizes of quantum dot only affect current and do not affect voltage. This result means that when an electron is transferred from the quantum dot to the TiO₂, it relaxes to the same conduction band level independent of the initial excitation energy. This exposes a fundamental issue with quantum dot solar cells; for current to flow, they need to transfer their energy to another larger species that will not be quantized in its energy levels. This means to make the most of the quantum dots quantization, the electron transfer needs to occur to a low level on the conduction band of the transporting species so that relaxation does not waste too much energy.

2.4 Conclusions and Next Steps

To help reduce these types of issues, the authors are looking into having multiple different-sized QDs layered onto the same cell to maximize absorption. If these so called "rainbow cells" are set up correctly, they can combine the benefits of large particles (being able to absorb a large range of wavelengths) as well as small particles (more efficient transfer of energy to substrate). They will also help with the aforementioned problem of the less flexible energy levels in the substrate (see Figure 8).

Overall, this paper helps to demonstrate how changing the size of quantum dots can have a significant effect on the properties of the cell. However, the authors were still only able to achieve a maximum power conversion efficiency (energy in the incident photons vs energy in the circuit) of 1%. This is much lower than that of currently available commercial cells which means that flexibility alone will not make these cells successful. Indeed, there also needs to be improvements to the injection of electrons from the quantum dots into the substrate, as well as the transport of the electrons through the structure of the cell.
3. Multiple Exciton Generation

Peak External Photocurrent Quantum Efficiency Exceeding 100% via MEG in a Quantum Dot Solar Cell

Semonin et. al.

3.1 Introduction and Motivation

One method of improving the efficiency of QD solar cells would be to turn the excess energy of high energy photons into multiple charge carriers. This is where multiple exciton generation (MEG) is useful. The next paper does not focus on the practical generation of useful energy, rather, it focuses on proving that one photon can generate multiple electron-hole pairs in the semiconductor. Semonin’s group was able to achieve external quantum efficiency (EQE) of over 100% [14]. Although counterintuitive, the definition of EQE is very important in understanding what an EQE greater than 100% actually means in terms of generated energy. It is also important to understand how this measurement is made. With this information, it is then possible to optimize the external quantum efficiency to a point where the only explanation for the efficiency must be multiple exciton generation.

The first important note is that EQE is not a measure of the amount of useful energy that can be generated from a system. Rather, it is the ratio of how many photo-carriers (i.e. electrons) are generated in the circuit per photon that hits the cell. Although this may seem like it would be what energy is usable, it is in fact any electron that the quantum dot injects into the circuit. This means it doesn’t take into account the energy of the photo-carriers themselves, so a low-energy electron (lower voltage) will result in the same quantum efficiency as an electron of higher energy. It also means that the importance of getting energy through the system is significantly reduced which has a large effect on the design of the solar cell.

3.2 Experimental

The cell itself was simpler than the one in the first Konkanand paper and involved layering various components as demonstrated in Figure 9. The gold layer was deposited using thermal evaporation, and as in the case of the first Konkanand paper, the quantum dots were applied by dipping the components into a solution of quantum dots. To maximize the number of deposited QDs, this process was repeated numerous times. Figure 9 illustrates the important components of the cell, with the glass covering the apparatus and the indium tin oxide acting as a transparent anode through which light must travel before hitting the PbSe quantum dots.

Although important, this process is not what allows this experiment to be successful in demonstrating MEG; the important process is the actual formation of the quantum dots. While previous experiments helped to demonstrate the importance of the size of the quantum dots themselves, this study goes further in exploring the effect of ligands on QDs. In QD solar cells, these ligands, which are chained organic molecules, serve multiple purposes. First, during the formation of the quantum dots, they help to ensure the stability of the dots. Long ligands such as oleic acid are useful in this stabilization step. However, after formation, the ligand must also be used in ensuring that the electrons excited in the quantum dots are moved to the external circuit (i.e. TiO2 substrate). In this second step, shorter ligands are preferable. For this reason, Semonin’s group decided to replace the longer oleic acid ligands with shorter ligands such as hydrazine. This can be done by adding the QDs to a solution with a high concentration of the target ligand. Since the dots have already formed, the stabilizing effect of the long chains in the formation process is no longer required and the effectiveness of the smaller chains in electron transport can be realized.

In testing the effectiveness of this method across a range of quantum dots sizes (varying band gaps), the EQE needed to be measured. This experiment accomplished this measurement simply by comparing current generated by the test cell to that generated by a reference photodiode with known efficiency. Each was exposed to the same monochromatic light source (Xe flash bulb with monochromater) so measured current could be converted to EQE. This eliminated the requirement for advanced spectroscopic equipment to determine the number of photons incident on the device. To further ensure that multiple exciton generation could be demonstrated, the experiment also measured internal quantum efficiency, which accounts for the light that the cell reflects and excludes it from efficiency calculations. Reflectance was measured with elipsometry, which involves having a detector that moves above the sample to determine how much light is reflected.

3.3 Results

With these tools, it is possible to obtain quantum efficiencies for a variety of quantum dots at various wavelengths (see Figure 10).

There is a great deal of information in Figure 10, however, what is of particular importance to this review are the 0.72eV bandgap plots (physically the largest quantum dots). At 3.44
eV (in the near UV), both the internal and external quantum efficiency exceed 100%. These values were greater than the absorptance (an intrinsic measure of the amount of radiation a material takes in, not to be confused with absorbance which is the extrinsic quantity that a spectrometer would measure). This means more electrons are generated than incident photons, which proves the existence of MEG in quantum dots cells. It is important to note that this does not imply that MEG does not occur at other wavelengths, just that it is the only possible explanation for the results at 3.44 eV. It is also important to note that the decline at the higher energies is due to the opacity in those regions of the ITO electrode and glass.

3.4 Conclusions and next Steps
Although Semonin’s group helps to demonstrate some of the useful properties of quantum dots, it still does not solve the issue of transporting the electrons generated though the system. Even with multiple exciton generation, maximum power conversion efficiency was 4.5%. This is a large improvement over Konkanand’s first paper in this review, however, the group still neglects to focus on the transport of the electrons through the system. This transport is a likely cause of a great deal of the lost energy.

4. Single walled carbon nanotubes

Single Wall Carbon Nanotube Scaffolds for Photoelectrochemical Solar Cells. Capture and Transport of Photo-generated Electrons

Kongkanand et. al.

4.1 Introduction
This transportation of electrons was the focus of Konkanand’s second paper in this review. This paper looked into using single walled carbon nanotube (SWCNT) scaffolds to facilitate the transport of electrons through a solar cell [15].

To understand their use in solar cells, it is first important to understand some of the properties of SWCNTs. Single Walled Carbon Nanotubes are graphene sheets with single atom thickness that have been joined at the end to form tubes (see Figure 11) [16].

![Figure 11. From [16], visualization of a single walled carbon nanotube](image)

There are a few properties of these structures that make them useful for QD solar cells. First, in either the metal type or semiconductor type tube configuration, electron mobility is excellent [16]. The tubes also have a great deal of strength and surface area which helps in the deposition of the quantum dots as well as any semiconductor to which the quantum dots inject electrons [16].

4.2 Experimental
Although these properties make them a good choice, there are a few drawbacks, one of the main ones being the difficulties in manufacturing SWCNTs [17]. Although methods are improving, they still require more advanced equipment than, for example, the manufacturing of quantum dots; the nanotubes used in this experiment were simply purchased from a commercial dealer [15]. To help ensure maximum performance, the SWCNTs were chosen after a comparison with those of other manufacturers for maximum purity and reasonable cost.

In terms of the rest of the experimental setup, the SWCNTs were electrically deposited as a thin film on carbon fiber and ITO electrodes. Since the paper focused on transport, the extra variables introduced by quantum dot choice were excluded. This means TiO$_2$, normally used as a substrate, was used as the light absorbing material itself. These particles, although small, are not as small as the actual quantum dots in the other papers and don’t have the same low bandgaps. Their large bandgap limits them in terms of producing useful energy from the Sun, since most solar radiation has an energy...
lower than the bandgap. However, what must be kept in mind is that this paper tried to maximize transport efficiency rather than power conversion efficiency. High energy electrons tend to lose more energy traveling through the system in terms of voltage [10]. This means that the preference for high energy electrons is a more difficult test for a transport medium than one using QDs, and the results should be extendable to use with QDs.

4.3 Results
This experiment showed marked improvement in numerous areas from traditional cells including the incident photon-to-charge-carrier efficiency, which means a higher number of electrons entered the nanotubes than did the in bare carbon fiber electrode. However, what is most relevant to this review is the improvement in the relationship between the current and voltage (see Figure 12)

![Figure 12](image)

Figure 12. Response of the current density of cells with and without SWCNT to changes in voltages. The SWCNT shows significantly improved response. Light and dark indicate whether the cell is irradiated.

Figure 12 demonstrates how the SWCNT cells are more responsive to voltage changes than cells without the tubes, which indicates the benefits of these devices in solar cells. This voltage response which was important in making this process could possibly be used to perform hydrolysis, which requires a large potential.

4.4 Conclusion and Next Steps
Although the improvements from other cells bode well for SWCNT based cells, the problem is that like the first two papers in this review, this paper focused on a certain aspect of the power conversion. Although a high voltage was achieved, meaning little energy was lost through the system, the actual power conversion efficiency was quite low (0.2%). With such a low efficiency the benefits SWCNT are not being realized.

5. Green Quantum Dots
High-Efficiency “Green” Quantum Dot Solar Cells
Pan et. al.

5.1 Introduction and Motivation
So far, this review has explored some of the important aspects of quantum dot solar cells, from the control of the dot size, to the use of multiple exciton generation and improvement of electron movement through the system. However, Konkanand and Semonin’s groups have not sufficiently focused on merging these aspects into a cohesive whole. They have also not focused on making the devices practical; for example, the CdSe nanoparticles contain cadmium, which is a toxic heavy metal [18].

The final paper used some of the principles learned in the first new papers, as well as some advances in quantum dot formation to create “green” quantum cells that make quantum dots solar cells more practical for commercial use. This also means there was a heavy focus on the experimental section.

5.2 Experimental
The main difference in the experiment from the first experiment in the first paper is the process for forming the quantum dots themselves. The changes in application to the substrate are minor and will not be discussed.

When making quantum dots with heavy metals, the process is relatively simple and can mostly be done in one reaction vessel with the addition of simple reagents. This because the heavy metals systems are not prone to defects in crystal structure upon formation. These defects cause problems with the transfer of electrons from the quantum dots into the substrate. Before this study, a common non-toxic QD material was copper indium sulfide (CIS) which has the downside of being prone to defects in crystal structure. To help alleviate this problem and therefore help improve efficiency, this study employed a hybrid quantum dot crystal coating CIS with ZnS (CID-Z).

To form these hybrid QDs, first the CIS quantum dots need to be made. This is done by both precisely controlled heating under Argon with a variety of stabilizing agents. These dots then need to be centrifuged to assist in purification before the zinc is added through zinc acetate with a precisely controlled time period. Even though this process is advanced than what is required for heavy metal quantum dots, it is still manageable and is may be scalable to commercial levels.

To determine if this technique was successful, numerous tests were used. Among these tests was transmission electron microscopy (TEM), which was performed to determine how well the CIS-Z QDs bind to the TiO₂ substrate. Transient absorption spectroscopy (rapid laser excitation pulse followed by probe pulse) was used to determine some of the important properties in the exciton formation process of the system to possibly explain reasons as to why the Zinc coating increases the effectiveness of the system. To determine some of the transport properties, electrochemical impedance spectroscopy was performed. Finally, typical tests of voltage and current were completed.
5.3 Results
Firstly, it was important to establish that the CIS-Z QDs bound to the TiO$_2$ as would occur in normal heavy metals QDs. The TEM results demonstrated this to be the case with excellent coverage of the TiO$_2$ with CIS-Z nanoparticles. Furthermore, the QDs were dispersed relatively evenly and were spherical, helping to indicate the success of the deposition process (see Figure 13).

![Figure 13. From [19], transmission electron micrograph of CIS-Z QDs (small spheres) deposited onto a TiO$_2$ structure.](image)

Knowing that the QDs adhered well, it could be determined whether there was an efficient absorption and injection of electrons from the QDs into the substrate. Transient absorption spectroscopy is useful in this instance, using this technique, it was possible to determine that the CIS-Z dots had superior performance in terms of electron injection and prevention of charge recombination (where the electron and positive hole meet up too early) to the CIS dots. It is also important to note that this was attributed to the reduction of surface defects. The electrochemical impedance spectroscopy agreed these results, with reduced charge recombination in the CIS-Z cells. It also showed that CIS-Z did not change the structure of the TiO$_2$ (see Figure 14).

![Figure 14. Transient absorption spectrum of the CIS-Z (blue) and CIS (red). The excitation pulse was at 388nm while the probe pulse was at 580nm. The slower decay in the CIS-Z cells shows reduced electron-hole recombination issues.](image)

Finally, to determine if all of this resulted in improved overall power conversion efficiency, the current per cm$^{-2}$ and voltage for the cell was measured under irradiation equivalent to solar radiation found at the Earth’s surface. These calculations lead to a power conversion efficiency of 6.66% which is a marked improvement over any other “Green” quantum dots and matches even the best of the heavy metal quantum dots.

5.4 Conclusions and Next Steps
It is clear that this study has demonstrated that it is possible to create efficient quantum dots without the use of toxic heavy metals. This was accomplished with an approach that considered all of the various steps in solar energy conversion, from photon capture to electron transmission. The next steps will be to make incremental improvements to the process until it can compete with silicon based photovoltaics.

6. Summary
The goal of any solar cell is to convert the energy offered by the Sun into some usable form. The four papers in this report help to demonstrate how quantum dot solar cells can achieve this goal.

The process starts with the quantum dots absorbing the Sun’s energy. The first concern is that the Sun’s energy is broad-spectrum. Traditional single junction bulk semiconductor based solar cells are limited by this fact, with their efficiency capped by the Shockley-Queisser limit [8]. The first study (by Kongkanand et al.) addressed this concern demonstrating the ability to control the absorption characteristics of quantum dots through simple size modification. This meant certain portions of the Sun’s spectrum could be easily targeted and since process of changing the size of quantum dots is relatively simple, it may be possible to have numerous QD sizes in one cell to achieve higher efficiency [10].

Along with collecting a broad spectrum, it is important that each photon collected creates as much electrical energy as possible. The next paper by Semonin et al. looked into proving one of the theorized benefits of quantum dots in being able to provide multiple charge carriers from one photon. This is a useful property that is also much more difficult to achieve with bulk semiconductors [20].

Finally, it is important to make sure that as much energy travels through the system as possible, and the paper by Kongkanand et al. in Nano Letters demonstrates how this can be accomplished through the use of single walled carbon nanotubes [17]. Knowing the importance of each individual step of solar energy conversion, it becomes possible to create a cell with greatly improved efficiency. Pan et al. created such a cell while reducing some of the drawbacks that are
problematic in the earlier QD cells, such toxicity to human health.

Although QD solar cells have promise, they are still a new technology and have serious limitations. There has still not been a commercialization of the cells and the papers have not scaled the technology up to commercially viable levels. This means that although the process of making the cells may be relatively simple it is, as with most new technologies, quite expensive. Also, although quantum dots are theorized to be quite stable once formed, and studies have looked at their stability, there has not been any testing to ensure the long term stability of the cells [21].

This review offers just a glimpse into the field of Quantum Dot solar cells. At the turn of the century, there were no functioning Quantum Dot solar cells and just 15 years later, cells are achieving power conversion efficiency approaching 10% [19]. This is a rapidly developing field that has a promising future, is ripe for future study and could help play a part in providing an alternative to fossil fuels.

7. References


