Application of Quantum Dots onto Glass Wafers as a Feasibility Test for the Spectral Down Conversion of UV Light for Solar Cells

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# Table of Contents

Acknowledgements ................................................................................................................................. ii

Table of Contents ....................................................................................................................................... iii

List of Figures ............................................................................................................................................... iv

List of Tables ............................................................................................................................................... v

1. Abstract .................................................................................................................................................... 1

2. Introduction ............................................................................................................................................. 2

  2.1 Realistic Constraints ........................................................................................................................... 3

    2.1.1 Health and Safety ........................................................................................................................ 3

    2.1.2 Manufacturability ........................................................................................................................ 4

3. Experimental Procedure .......................................................................................................................... 4

  3.1 CdSe Quantum Dot Synthesis ............................................................................................................ 4

  3.2 Solar Cell Testing ................................................................................................................................ 6

  3.3 Spin Coating Process .......................................................................................................................... 7

4. Results ...................................................................................................................................................... 9

  4.1 Solar Cell Analysis with Addition of Quantum Dots ........................................................................... 9

  4.2 Spin Coating Application and Spectroscopy ..................................................................................... 14

5. Discussion ............................................................................................................................................... 18

  5.1 Solar Cell Enhancement ................................................................................................................... 18

  5.2 Quantum Dot Adhesion ................................................................................................................... 19

6. Conclusion .............................................................................................................................................. 21

7. References .............................................................................................................................................. 22
List of Figures

Figure 1: Metal spatula can measure cadmium without static cling. .......................................................... 5
Figure 2: Fully submerged $\text{N}_2$ needle will produce violent bubbling when set correctly. ......................... 5
Figure 3: Syringe is drawn while bottle is pressureized. .............................................................................. 6
Figure 4: Solar cell with quantum dots in a contained petri dish with .............................................................. 7
Figure 5: Spin coater with glass wafer centered and suctioned for processing. .............................................. 8
Figure 6: Glass wafer is set right above fiber optics (left). UV lightsource is then ......................................... 8
Figure 7: I-V curve of solar cell with an empty petri dish under the halogen lamp........................................ 10
Figure 8: I-V curve of solar cell with an empty petri dish under UV pen light .............................................. 10
Figure 9: I-V curve of solar cell with QDs under UV pen light ......................................................................... 11
Figure 10: I-V curve of solar cell with QDs under halogen lamp ................................................................. 11
Figure 11: I-V curve of solar cell with QDs under both halogen and UV pen light ......................................... 12
Figure 12: I-V curve of solar cell free of QDs under high powered UV lightsource. .......................... 13
Figure 13: I-V curve of solar cell with QDs under high powered UV lightsource ......................................... 13
Figure 14: Spectrometer reading of glass wafer after first application of quantum dots. ......................... 15
Figure 15: Spectrometer reading of glass wafer after second application of quantum dots ...................... 15
Figure 16: Spectrometer reading of glass wafer after third coating of quantum dots .................................. 16
Figure 17: Spectrometer reading of glass wafer after fourth coating of quantum dots .............................. 16
Figure 18: Spectrometer reading of glass wafer after fifth application of quantum dots .......................... 17
Figure 19: Tetrahedral SiO$_4$. All oxygen atoms are shared by other silicon atoms thus the chemical formula of this molecule is SiO$_2$. ........................................................................................................ 20
## List of Tables

Table I: Comparison of Power Readings from Solar Cell Testing ............................................................... 12
Table II: Solar Cell Analysis Using UV Lightsources ...................................................................................... 14
1. Abstract

Quantum dots have the ability to convert high energy photons into multiple lower energy photons. Down conversion of such high energy photons from sources such as UV light can be beneficial for applications on solar cells which waste much of the energy in the form of thermalization. To test this theory, a solar cell was hooked up to an Amprobe Solar Analyzer and tests were run to compare power output with and without the presence of quantum dots. Additionally, quantum dots were spin coated onto a glass wafer to determine its adhesion ability. Spectrometer readings were taken of the wafer after each spin coating cycle to measure any change in fluorescence. Power output of the solar cell without quantum dots was measured to be 224.1 mW while power output of the solar cell in the presence of quantum dots was 200.6 mW. Furthermore, spectrometer readings showed that no significant increase in fluorescence was gained after spin coating the glass wafer with quantum dots. These results led to the conclusion that the use of quantum dots suspended in a liquid medium are not effective in enhancing the performance of solar cells. Poor results may be due to the use of quantum dots emitting photons that still contain energy greater than the band gap of silicon. In addition, spin coating of the quantum dots is not a plausible method for application since very little adhesion took place. Lack of adhesion can be attributed to polar and non polar interaction between the glass wafer and quantum dots in octadecene respectively. Future steps include testing on a smaller scale using a silicon photodiode, using red quantum dots which contain photons closer to the silicon band gap, and suspending the dots in a different medium to help adhesion.

Keywords: Materials Engineering, Nanotechnology, Quantum Dots, Solar Cells, Solar Cell Efficiency, Spectral Down-conversion
2. Introduction

Current single-junction solar cells can only efficiently convert photons of energy that are close to the band gap of the semiconductor material ($E_g$). Photons with energies ($E_{ph}$) lower than that of the semiconductor band gap are transmitted and none of the energy is utilized by solar cell. Photons with energy larger than the band gap are able to excite valence electrons, but their excess energy ($E_{ph} - E_g$) is wasted in the form of thermalization.\textsuperscript{1} Thus, a significant portion of photon energy that comes from sunlight is wasted as it is converted into heat instead of electricity by a solar cell. Quantum dots (QDs) are a potential remedy to this problem due to their ability to function as spectral down-converters. Quantum dots are nano-sized particles which, at their small size experience distinct and segregated band gaps known as quantum confinement. These discrete band gaps increase in energy level as particle size decreases.\textsuperscript{2} An advantage of using QDs for down-conversion is that emission of photons happens as a two-step process. This means that potentially, a photon with double the energy of the band gap can be absorbed by a QD, and emitted into two photons with exactly the energy needed to excite electrons in the solar cell.\textsuperscript{3} Spectral down-conversion can therefore increase the effectiveness of a solar cell by making sure photon energy is used as efficiently as possible in generating power.

The experiment proposed then, is to determine whether CdSe quantum dots suspended in a liquid medium are able to function successfully as spectral down-converters and, whether spin coating of said quantum dots is a feasible method of application onto solar cells. Past experiments conducted by Cal Poly students revealed that when quantum dots were suspended in a microfluidic array and excited by a UV light source, irradiance to the receiving solar cell increased by only 4.8 mW/m\textsuperscript{2}. This small increase in irradiance was attributed to low concentration of QD found in the array due to shallow channels and a low fill factor.\textsuperscript{4}
In order to better assess the theory of using quantum dots as spectral down-converters, an ideal simulation will be setup where an abundance of quantum dots will be present on top of a solar cell. To test the application method, QDs will be injected onto a glass wafer during spin cycle. Adhesion of any QDs will be determined by measuring the fluorescence of the wafer after spin coating using a UV lightsource and spectrometer.

### 2.1 Realistic Constraints

#### 2.1.1 Health and Safety

A big concern over nanoparticles such as CdSe quantum dots is their adverse effects to the human body. Specifically, quantum dots can be cytotoxic which means they are hazardous to cells. In a study with rats exposed to uncoated CdTe QDs, a concentration of 1 µg/mL was enough to cause cytotoxic damage to their pheochromocytoma cells. How QDs kill cells isn’t clearly known, however, it is believed to be connected to the presence of free Cd from QD degradation. The study with the rats pertains to this experiment in that CdSe QDs are used and thus if by any means ingested can also be susceptible to QD degradation and cytotoxicity. Furthermore, during manufacturing of QDs, possible exposure to cadmium oxide through inhalation is possible. Inhalation of the cadmium powder can cause both pulmonary and kidney diseases to arise.

Protective equipment such as gloves, goggles, and a fume hood were used to prevent direct skin contact and inhalation of fumes from occurring. In addition, careful handling of the cadmium oxide and selenium powder was crucial in making sure no particles became airborne.
All chemical waste from quantum dot manufacturing was kept in a liquid waste containment meant specifically for QD synthesis.

2.1.2 Manufacturability

QD synthesis during the project was achieved at varying levels of success due to poor repeatability. This problem stemmed from the use of inconsistent equipment such as the hotplate used to heat the chemicals. QD synthesis is a very time and temperature sensitive process and so using a hotplate that could not keep a consistent temperature made it difficult to obtain the desired size of QDs. Contamination of chemicals was also possible as flasks and needles are reused for each synthesis. To mitigate cross contamination, all equipment and needles were rinsed in acetone and water however, it is possible some residue can remain especially on the surface of the fume hood where the needles are laid when not in use.

3. Experimental Procedure

3.1 CdSe Quantum Dot Synthesis

Manufacturing of CdSe quantum dots was done under standard Cal Poly protocol. Modifications to the procedures were done in quantity of chemicals used to increase batch size and changes in temperature due to inconsistent heating from the hotplate. Standard operation dictates that for the selenium trioctylphospine (Se-TOP) precursor, 33mg of selenium is weighed into a plastic weigh-boat and transferred into a two-neck round bottom flask. Likewise, for the cadmium (Cd) precursor, 13 mg of cadmium oxide powder was weighed out and put into a three-neck round bottom flask. A slight modification during the experiment was to weigh the
cadmium oxide powder onto a metal spatula to prevent static clinging of the powder during weighing (Figure 1).

**Figure 1:** Metal spatula can measure cadmium without static cling.

Once weighed out, a stir bar was put into each flask and sealed with rubber stoppers at each neck. For the Se-TOP, trioctylphospine (TOP), octadecene (ODE), and the two-neck flask were purged by inserting \( \text{N}_2 \) gas needles and vent needles into the rubber stoppers. It is important to note that for the liquid chemicals, the \( \text{N}_2 \) needles need to be submerged (Figure 2).

**Figure 2:** Fully submerged \( \text{N}_2 \) needle will produce violent bubbling when set correctly.

After 15 minutes, the \( \text{N}_2 \) needles were taken out of the liquid and labeled syringes were used to create positive pressure inside each container; afterwards both the \( \text{N}_2 \) gas needles and vent needles were removed (Figure 3).
Using the syringe specified for ODE, 5 mL of octadecene were added to the flask and then it was lowered into an oil bath set to 150 Celsius. Next, 0.4 mL of TOP was added to the flask and was left in the oil bath until the precursor was optically clear. For the Cd precursor, oleic acid, ODE and three-neck flask were purged using the same process. The flask was lowered into the oil bath set at 220 Celsius and combined with 10 mL of ODE and 0.6 mL of oleic acid. Once the Cd precursor was optically clear, the oil bath was set to about 225 Celsius and 1 mL of the Se-TOP precursor was added to the Cd flask. CdSe samples were extracted at desired time intervals such as 0, 30, 60, or 90 seconds via a non-disposable glass syringe into glass vials. After cooling, samples were examined under UV light for quality.

### 3.2 Solar Cell Testing

Testing of a small scale solar cell was done to compare the effectiveness of the quantum dots in ideal conditions. These conditions included having an abundance of QDs “adhering” to the solar cell which in this case meant encasement of QDs in a petri dish placed on top of the solar cell. To initiate testing, the leads located on the solar cell were attached to clamps leading
to the Amprobe. The Amprobe was able record an I-V curve of the solar cell and transfer them to a laptop running the Solar Module Analyzer software. For this experiment, a halogen lamp was used as a substitute source of sunlight. Furthermore, a UV pen was used to excite the quantum dots into fluorescence. Depending on what scenario was to be tested, any combination of lights were used as well as the inclusion of the petri dish of QDs (Figure 4)

![Figure 4: Solar cell with quantum dots in a contained petri dish with the halogen lamp above and UV pen held at the side of the petri dish.](image)

### 3.3 Spin Coating Process

Spin coating of the quantum dots onto the glass wafer and subsequent spectroscopy was done under no standard operating procedure. To coat the wafer with QDs, the wafer was laid and centered onto the spin coater’s vacuum chuck (Figure 5).
Figure 5: Spin coater with glass wafer centered and suctioned for processing.

Next, a program was picked from the spin coater’s user interface. For this experiment, the program consisted of a 30 second application phase at 500 rpm which lead to a minute long drying cycle at 500 rpm. Once application of the QDs was finished, the wafer was taken to a custom made fixture where it was laid onto the center of the fixture and a UV lightsource was put over it (Figure 6).

Figure 6: Glass wafer is set right above fiber optics (left). UV lightsource is then positioned on top of custom fixture (right)

An Avantes spectrometer was attached to a fiber optics cable which was held beneath the UV lightsource fixture. It is important to note that the fiber optics cable had a narrow band pass filter
attached to prevent the UV light from interfering with spectrometer readings. When the UV lightsource was activated, the spectrometer was able to take real time data of the wavelength and intensity of light that emerged from the coated wafer. The data was transferred to an excel file for further analysis.

4. Results

4.1 Solar Cell Analysis with Addition of Quantum Dots

The solar cell testing consisted of several scenarios to help observe any change in the $P_{\text{max}}$ generated by the solar cell. Initial scenarios included:

1. Solar cell with empty petri dish under halogen lamp
2. Solar cell with empty petri dish under UV pen light
3. Solar cell with QD filled petri dish under UV pen light
4. Solar cell with QD filled petri dish under halogen lamp
5. Solar cell with QD filled petri dish under halogen and UV pen light

Scenario 1 was done as a control to compare any effects the QD had on the solar cell for scenarios 4 and 5. Testing the solar cell without QDs with the UV pen was meant to determine if the UV pen would create any noticeable signal on the analyzer. Likewise, testing the solar cell with QDs present with only the UV pen was meant to observe if the excitation of the pen alone on the QDs was enough to create a power reading. These scenarios were successfully tested with the Amprobe and produced the following I-V curves.
Figure 7: I-V curve of solar cell with an empty petri dish under the halogen lamp.

Figure 8: I-V curve of solar cell with an empty petri dish under UV pen light.
3. I-V Curve of Solar Cell with QDs under UV Pen Light

Figure 9: I-V curve of solar cell with QDs under UV pen light.

4. I-V Curve of Solar Cell with QD and Halogen Lamp

Figure 10: I-V curve of solar cell with QDs under halogen lamp.
Although some amount of variance was expected when using the solar analyzer, the results show that adding quantum dots to the solar cell did not improve its performance. Comparing scenario 1 which had no QDs and scenario 5 which utilized excited QDs, the max power produced by scenario 1 is still 11.7% greater. Likewise, we see that for scenario 2 and 3, no power reading was measured regardless of the inclusion of quantum dots. These results seem to oppose the theory that quantum dots can enhance solar cell efficiency. A possible reason for this was that the UV pen simply did not output enough light to optimally excite the liquid quantum dots.
Hence, the next step in testing was to use a high powered UV lightsource to increase QD excitation.

**Figure 12:** I-V curve of solar cell free of QDs under high powered UV lightsource.

**Figure 13:** I-V curve of solar cell with QDs under high powered UV lightsource.
<table>
<thead>
<tr>
<th>Solar Cell Test</th>
<th>With QD</th>
<th>Without QD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{mp}$ (mA)</td>
<td>0.2 mA</td>
<td>0.2 mA</td>
</tr>
<tr>
<td>$V_{mp}$ (V)</td>
<td>1.837 V</td>
<td>1.619 V</td>
</tr>
<tr>
<td>$P_{max}$ (mW)</td>
<td>0.367 mW</td>
<td>0.323 mW</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.057 %</td>
<td>0.050 %</td>
</tr>
</tbody>
</table>

Testing with the more powerful UV lightsource revealed that the excited quantum dots were still unable to produce a change in solar cell power output. The table above shows that the $P_{max}$ between the two scenarios varied about only 12% with the $P_{max}$ of the solar cell using the QDs being lower once again.

4.2 Spin Coating Application and Spectroscopy

To test how well the quantum dots would adhere to a glass wafer after spin coating, a spectrometer reading was done to the wafer after each spin cycle. An increase in fluorescence after each cycle was desired as it would support spin coating as a feasible application method. The quantum dots used were manufactured to have a green fluorescence and so a peak at the 550 nm wavelength was desired. The following graphs show experimental results after applying 5 coatings of QDs at a 500 rpm drying cycle.
**Figure 14:** Spectrometer reading of glass wafer after first application of quantum dots.

**Figure 15:** Spectrometer reading of glass wafer after second application of quantum dots.
Figure 16: Spectrometer reading of glass wafer after third coating of quantum dots.

Figure 17: Spectrometer reading of glass wafer after fourth coating of quantum dots.
Figure 18: Spectrometer reading of glass wafer after fifth application of quantum dots.

With low counts and a lack of a peak at 550 nm, the graphs illustrate to us that no adhesion of quantum dots took place during the spin cycles. Visual inspection of the wafer after spin cycling revealed a faint green fluorescence however, the amount of light produced was insignificant and was not picked up by the spectrometer. Without a form of adhesive, it seems that the quantum dots simple slid off the glass wafer. No further tests were conducted because a 500 rpm dry cycle was the lowest setting the spin coater could operate on and a faster rpm would only translate to a greater amount of QDs slipping off.
5. Discussion

5.1 Solar Cell Enhancement

Results from solar cell testing led to the conclusion that the petri dish with quantum dots did not improve solar cell performance. However, solar cell performance is affected by many factors – any which could have decreased the power output of the solar cell during testing. For instance, as temperature increases, the band gap of the semiconductor shrinks. The shrinking of the band gap allows for lower energy photons to be able to excite semiconductor electrons and thus potentially increases current. However, a higher temperature also decreases voltage because more electrons are released at a lower potential. Because $P_{\text{max}} = \text{current} \times \text{voltage}$, an increase in temp can manipulate power output either way.$^8$ In the case of this experiment, a silicon single-junction solar cell was used with a halogen lamp. Silicon has a band gap of 1.1 eV, while the majority of spectral intensity from a halogen lamp lies between 650 nm to 900 nm. Using Equation 1:

$$E = \frac{hc}{\lambda}$$  \hspace{1cm} \text{Equation 1}

Where h is Planck’s constant at $6.626 \times 10^{-34}$ joule-s and c is the speed of light at $2.998 \times 10^8$ m/s, we see then that the energy of the photons in a halogen lamp range from 1.38 eV to 1.91 eV.$^9$ Since even the minimum photon energy from the halogen lamp contains enough energy to excite valence electrons of the silicon solar cell, we can say that the increase of temperature would have no effect on the solar cell’s current. However, the potential of each freed electron still drops and so voltage still decreases with heat – meaning that under a halogen lamp, the solar cell will decrease in power output as temperature rises. During testing, the solar cell was left
under the halogen lamp for the entire duration. Furthermore, testing of the solar cell with QDs present came last and so it is not hard to imagine that the solar cell increased had increased in temperature by the time we tested it with quantum dots. This is one possible explanation as to why solar cell efficiency decreased when the opposite should have occurred.

Another factor that could have affected solar cell performance during QD testing is that the quantum dots are not as optically transparent as air or translucent as the glass form the petri dish. The fact that the quantum dots suspended in octadecene are less translucent comparatively means that less light is able to pass through the medium as more of it is either scattered or absorbed.10

Additionally, green quantum dots are not optimally suited for enhancing solar cells because their photon emission is at 550 nm or 2.25 eV. Since silicon has a band gap of 1.1 eV, the green light that is emitted will still cause thermalization and thus inefficient conversion of photon energy to electricity by the solar cell.

### 5.2 Quantum Dot Adhesion

By not using any form of adhesive, the application portion of the experiment was at the whim of the interaction between the quantum dot molecules and the silica glass wafer molecules. Silica, also known as silicon dioxide, is a tetrahedral shaped molecule with the silicon atom being at the center and the four oxygen atoms at the vertices of the tetrahedron (Figure 19).
Due to the strong (but varying) electronegative forces of silicon and oxygen, these molecules are considered to be polar. Unlike glass, octadecene is not a nonpolar molecule and is hydrophobic. Nonpolar molecules do not interact well with polar molecules and thus, during spin coating the octadecene had a greater tendency to slip off. A possible remedy for this would be to encapsulate the quantum dots with a function group that has a nonpolar tail to attach to the quantum dot molecules, and a polar head to help attach to polar surfaces such as water or glass.
6. Conclusion

Although the experiment did not yield any results that can confirm solar cell enhancement through quantum dots, or spin coating as a viable application method, changes to the experiment can improve future outcomes. Researching function groups that can help attach QDs to polar surfaces or, an adhesive non detrimental to the dots can be possible methods of application. Doping of the quantum dots into silicon wafers is another utilization of the nano particles that may prove more successful. Using a different medium to put the quantum dots in can help ascertain if the octadecene had any effects on past results. In regards of the solar cell testing, future steps should comprise of using red quantum dots instead of green and taking the test to a smaller scale by using a silicon photodiode. Measuring the current produced from a photodiode would be more sensitive and thus changes will be easier to spot.
7. References


