

Improving Solar Cell Performance Using CdSe/ZnS  
Core/Shell Quantum Dots in a Spectral Conversion  
System

BY

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June, 2012

## Abstract

Solar cells have been found to absorb light more efficiently and effectively when the energy of incoming photons matches the electronic band gap of the solar cell. Spectral conversion of light from UV to lower energy wavelengths can improve solar cell efficiency an estimated 14.5%. Cadmium Selenium/Zinc Sulfide Core/Shell quantum dots have been successfully embedded in PDMS silicone elastomer. Using a Keithley 2400 Electrometer with Labview software, voltage and current characteristics have been recorded in steps of 10 mV with a wait time of 250 ms on a commercially available solar cell using an artificial solar spectrum created by a Tungsten Halogen lamp. The commercially available solar cell was found to have a maximum power output of 250 mW and a fill factor of 71.025%. Short term repeatability testing and long term reproducibility testing was conducted using a sample size of ten and a wait time of 1 hour and 1 day respectively, repeated five times. The system was found to have a long term reproducibility of 0.010% and a short term repeatability of 0.004% after a one hour warm-up period to reach a thermal equilibrium. Three mechanisms of light attenuation have been observed due to PDMS: the addition of interfaces, surface adhesion, and thickness. The most substantial loss was created by the addition of interfaces which decreased the fill factor of the solar cell by 0.00839 or 1.18%. Losses from surface adhesion and losses due to increasing thickness were minimal. The CdSe/ZnS core/shell quantum dots used fluoresced at a wavelength of 570 nm. These quantum dots were dried from octadecane and then suspended in toluene before being mixed with bulk PDMS to create the spectral converter. The spectral converter increased short circuit current by 1% and did not change open circuit voltage or fill factor. The maximum power was increased to be equal to that of the bare solar cell.

Keywords: Spectral Converter, Solar Cell, Quantum Dots

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## Acknowledgements

I would like to thank the many people who helped me reach this point: Dr. R. Savage for his guidance and support in both academic and personal direction, Dr. Bob Echols for his help in creating a solar cell characterization system, The MatE faculty for the education that gave me the knowledge to undertake this project and for the self-reflection that allowed me to grow as an individual, My friends here at CalPoly and abroad for their unquantifiable amounts of support, And finally, my loving mother Julie Brooks, for her unending support.

## Introduction

### Realistic Constraints

In 1961 William Shockley and Hans Queisser proposed that a single junction solar cell under the illumination of the sun could achieve a maximum of 30% efficiency.<sup>1</sup> The majority of this loss is attributed to the thermalization of electrons excited beyond the band gap of silicon (Figure 1). The response to their limit was to create a solar cell with multiple band gap energies or to use a spectral converter to shift the energy of the sun's spectrum into easily absorbed monochromatic light.<sup>2</sup>

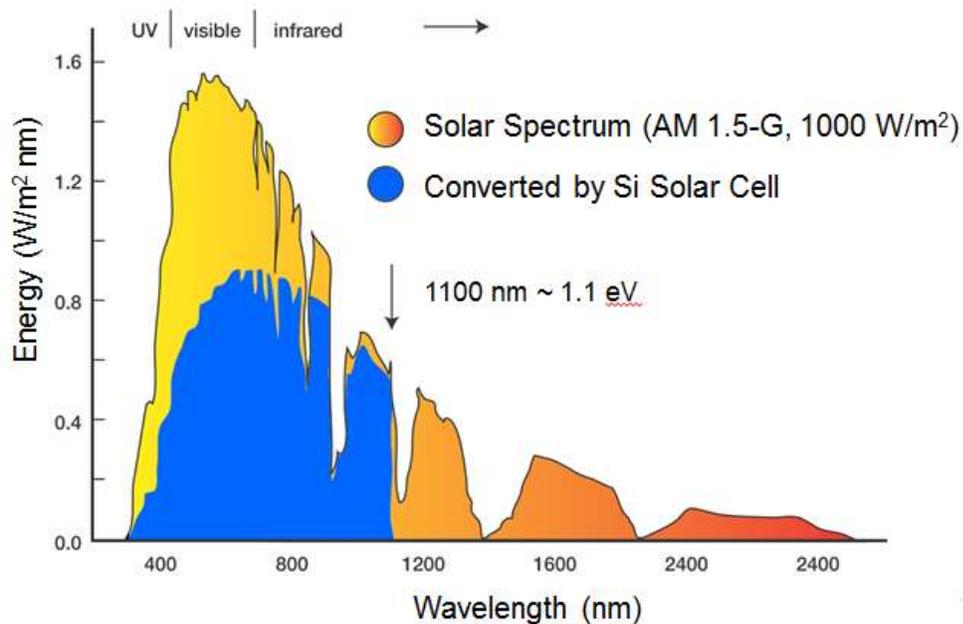


Figure 1: The Shockley Queisser Limit applied to the solar spectrum.<sup>3</sup>

### Environmental

Approximately 48% of electricity in the US is generated by centralized coal power plants. When coal power generation is combined with natural gas, non-renewable resources account for nearly 70% of all electricity generated in the United States.<sup>4</sup> Peak coal, the point in time at which the maximum global coal production rate is reached, is projected to be sometime near 2025 at 30%

above the current extraction rate.<sup>5</sup> Once these resources run out, other sources of electricity must be in place to avoid an economic and social crisis. Two major options for power generation are nuclear energy, and solar energy. Nuclear energy requires centralized power generation sites, which require distribution networks or “grids.” These grids have some level of attenuation as well as infrastructural costs. The less centralized a power generation method is, the lower the costs associated with distribution become. Photovoltaic based solar power generation methods can be site specific or centralized, which allows for optimization of economic factors with energy loss.

## **Economic**

All methods of energy production have an associated levelized energy cost (LEC or LCOE) which takes into account the investment expenditures, maintenance expenditures, and fuel expenditures in relation to the energy produced over the product’s life time.<sup>6</sup> This measure standardizes the costs of an energy production method per unit of energy. A favorable LEC will exert economic pressures towards adopting any given method; however, care must be taken when evaluating the LEC since the underlying assumptions of the calculation can create false results. Since the LEC is essentially all of the costs over the lifetime of the product divided by all the energy produced during that lifetime, a successful design would lower the LEC of the product. In the case of solar energy, the majority of the cost to the customer is in the initial investment, with almost no maintenance costs and no fuel costs. The cost of the unit does not increase substantially over time, which means improving the LEC of solar energy can be achieved by decreasing the initial cost of the solar cell, extending the lifetime of the unit, or by increasing the amount of energy the unit can produce. Most solar systems are robust and have extensive lifetimes. Since mass production already lowers the initial cost, increasing the efficiency of the solar cell is the most viable option for improving the LEC.

## **Single Crystalline Solar Cells**

Solar cells convert light into electricity through the photovoltaic effect. Energy from the sun, in the form of photons, is either reflected, absorbed, or transmitted by the solar cell. The photons that are absorbed by the photovoltaic cell excite electrons within the semiconductor material which

can then create electric current in a circuit.<sup>7</sup> The amount of potential energy each exciton may possess is fixed by the band gap of the semiconductor used. Single crystal silicon has a band gap of 1.1 eV, so each exciton will have 1.1 eV of potential energy.<sup>8</sup> All wavelengths that are more energetic than the band gap of the material may be absorbed. As light is absorbed by a solar cell, the characteristic curve of the solar cell shifts upwards and increases the current in the circuit (Figure 2). Each absorbed photon can only create one exciton. Light from the sun is a spectrum which contains a predictable amount of light in a distribution of wavelengths. Each wavelength has discrete amount of energy.

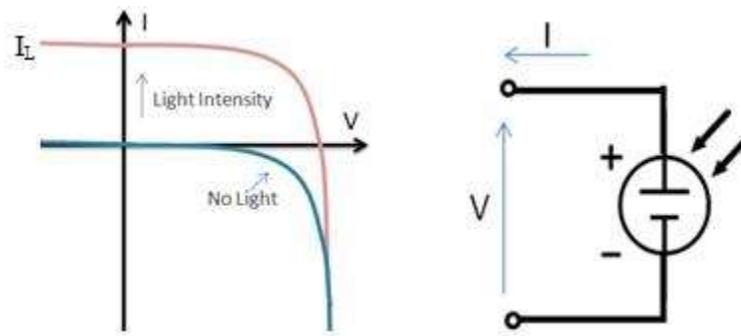


Figure 2: Illumination of the solar cell creates an upward shift in the characteristic curve of the solar cell.<sup>9</sup>

### Characterization

Each solar cell, or solar cell system, produces a characteristic voltage and current curve. Several values on this curve are of interest as they aid in characterizing the solar cell's equivalent circuit (Figure 3).

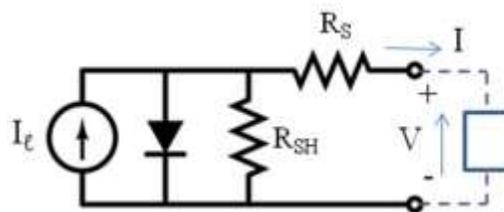
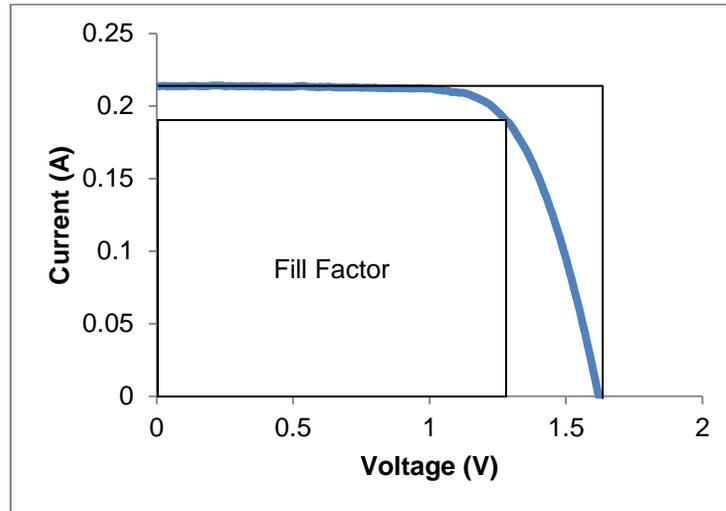


Figure 3: Equivalent circuit of a solar cell.<sup>9</sup>

The x-intercept defines the open circuit voltage of the solar cell and is characteristic of the material used. The y-intercept defines the short circuit current and generally illustrates the

illumination level. The maximum power is the largest power that is produced by the system. Finally the fill factor is created by taking the ratio of the maximum power produced and the product of the open circuit voltage and short circuit current (Figure 4).



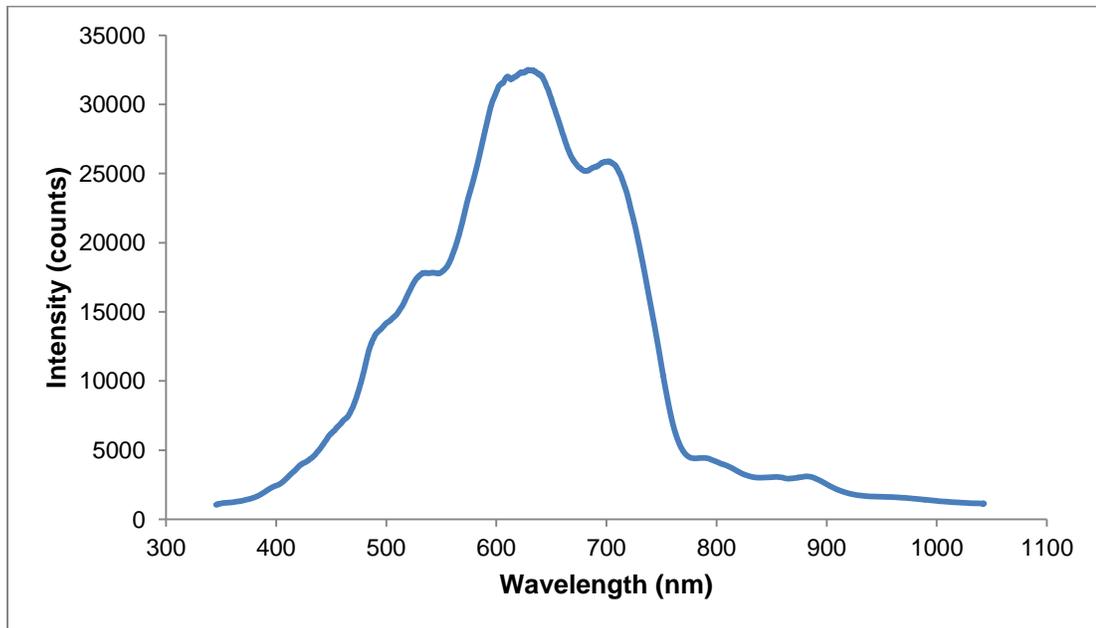
**Figure 4: Characteristic voltage and current curve for a solar cell.**

In reality not all the incoming photons are absorbed and not all of the excitons created have energy of exactly 1.1 eV or even survive long enough to become useful. The number of photons a material absorbs can be described by the external quantum efficiency (EQE).<sup>10</sup> In an ideal world the EQE of a semiconductor material would be a step function; however, the world is rarely ideal. A more realistic model of EQE would be a shifted distribution, peaking below 100% at the band gap of the material. Since the appropriately energetic photon for silicon has a wavelength of 1100 nm, most of the energy from the sun is wasted. Both the efficacy of absorption, EQE, and the efficiency of conversion, increase as the energy of incoming light approaches the band gap energy, it becomes energetically favorable to down convert photons. The specific emission wavelength that optimizes the system, changes in response to both the EQE of the solar cell and the efficiency of the solar cell and thus a spectral conversion system must be incredibly flexible. Early spectral converters used organic dyes to achieve this, but the dyes lacked the precision needed to optimize the system effectively.<sup>2</sup> Recent advances in quantum confinement structures, specifically quantum dots, have revitalized this area of research. Quantum dots allow precise tuning of their band gap structure based on size. Quantum dots also have the added benefit of

high absorption well into the UV spectrum making them the perfect candidate for spectral conversion.

## Methods and Materials

In order to maximize the response of the solar cell to the spectral converter and to minimize the number of variables being observed in the experiments, experimental controls were used. A single commercially available solar cell was used for every experiment. If multiple solar cells were used there was a chance that small differences in the each solar cell's performance might have interfered with an observed response from the active variables in the experiment. Even though this system was designed to be used as a solar spectral converter, a tungsten halogen artificial light source was used in all experiments (Figure 5).



**Figure 5: Spectrum of the Tungsten Halogen light source used.**

Although the Tungsten Halogen light source is not an ideal replication of ASTM G173 solar spectrum, it was similar enough to serve as a proof of concept. It should be noted that the artificial light source used is less energetic than ASTM G173 and as such the gains exhibited by

the spectral converter in this study are less pronounced than if the system were in use under actual sunlight (Figure 6).

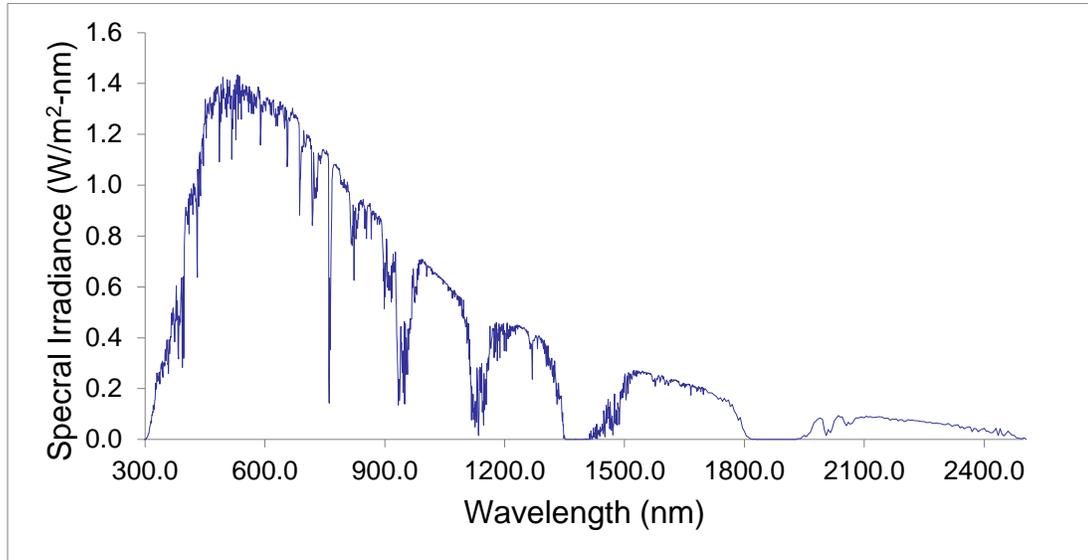


Figure 6: ASTM G173 standard solar spectral emission at 1000 W/m<sup>2</sup> nm.<sup>11</sup>

## Sample Preparation

The silicon based polymer Polydimethylsiloxane (PDMS) was used as the primary encapsulant for the spectral conversion system.<sup>12</sup> The PDMS was produced using Dow Corning Sylgard® 184 with a 10:1 ratio of bulk elastomer to curing agent. Once the two components were mixed together, the mixture was placed into a vacuum chamber to remove any entrained air. The mixture was then poured into its final casting container, degassed a final time, and placed in a furnace at 70°C for three hours, or until sufficiently cured. This was repeated to create a 1.38 mm thick sample and a 4.58 mm thick sample. The spectral converter was produced using the same procedure; however, the solution of colloidal quantum dots in toluene was added before the final degassing step.

Quantum dots were used as the active component of the spectral converter. Quantum dots were chosen because their band gap is tunable based on their size.<sup>13</sup> The quantum dots used were produced using a bulk synthesis in the Cal Poly nanofabrication lab.<sup>14</sup> The final product of the bulk synthesis was a colloidal suspension of CdSe/ZnS core/shell quantum dots in a solvent of

octadecane. Octadecane dissolves PDMS, therefore it was necessary to remove the quantum dots from the octadecane, and suspend them in toluene. Although toluene is not ideal, the only difficulty that arose was dispersing the quantum dots evenly, which was remedied using thorough mixing procedures and mixing via the degassing step.

## Equipment Testing

The accuracy and precision of the automated testing apparatus used was determined using long-term reproducibility and short-term repeatability testing. The long term testing was conducted over five days with ten tests each day. The short term testing was conducted over five hours with ten tests each hour. The characteristic data was extracted from the voltage and current curves using a custom java based program. The fill factor was chosen as the response variable since fill factor takes into account short circuit current, open circuit voltage, and the maximum power point. The system was found to have a long term reproducibility of 0.010% and a short term repeatability of 0.004% based on a 95% confidence interval.

## Experimental Controls

Several unavoidable factors were observed during this study. The first, and most apparent, was the imperfect adhesion of PDMS onto the solar cells surface. This imperfect adhesion created additional interfaces for the light to penetrate (Figure 7). In order to minimize this, each sample was cleaned with isopropyl alcohol, adhered to the surface, and placed in a vacuum chamber. The vacuum caused the air trapped between the PDMS layer and the solar cell to expand and escape.

The second observed factor was a thermal shift over time. In order to combat this thermal shift, a one hour warm up step was added to all experiments so the samples could reach quasi-equilibrium with the room. The solar cell regularly reached temperatures of 65°C which decreased overall performance. It is recommended that an isothermal test bed be used in future testing.

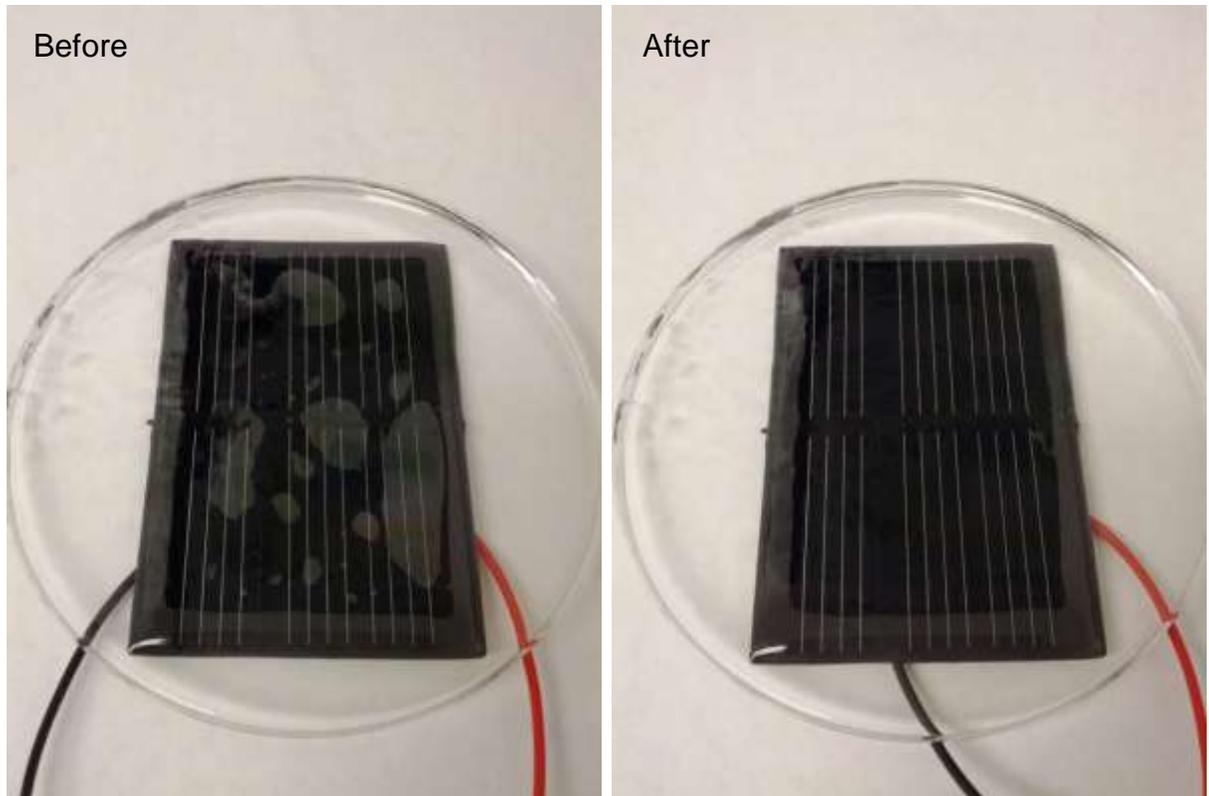


Figure 7: Cleaned PDMS sample applied to a solar cell before and after the degassing procedure.

## Results

The standard solar cell used was found to have a high quality characteristic curve. The short circuit current was pulled directly from the data set and was found to be 233 mA (Figure 8). Using linear interpolation, the open circuit voltage was found to be 1.61 V. The maximum power output was found to be 250 mW, creating a fill factor of 71.025% (Figure 9).

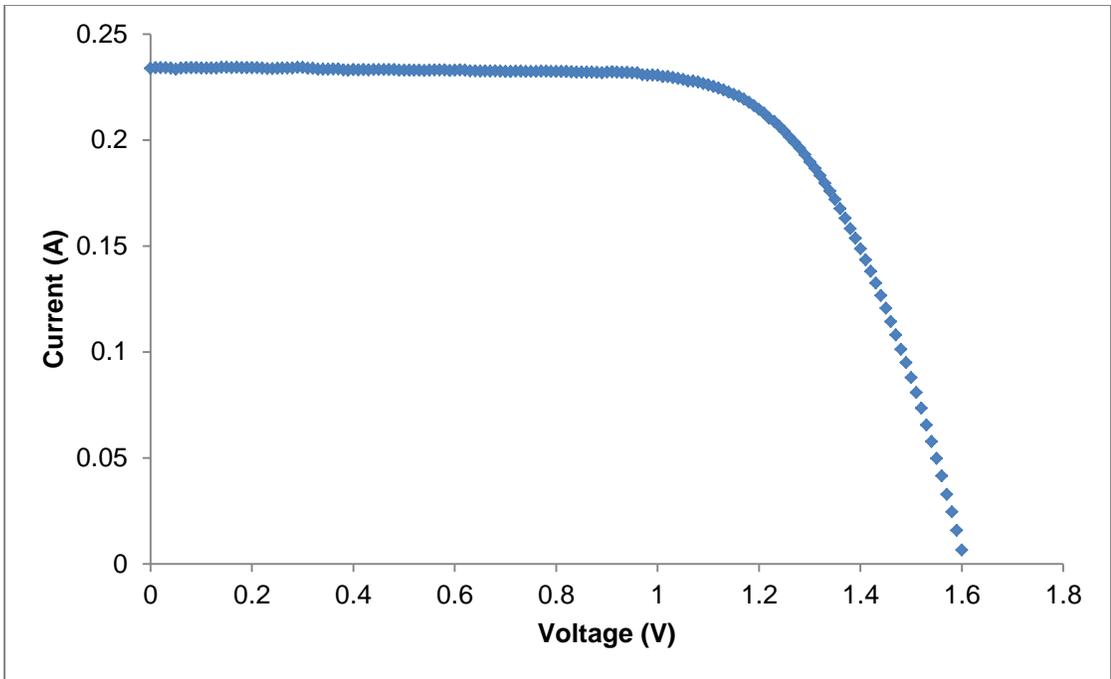


Figure 8: Characteristic voltage and current curve for the standard solar cell showing the frequency and regularity of the data points.

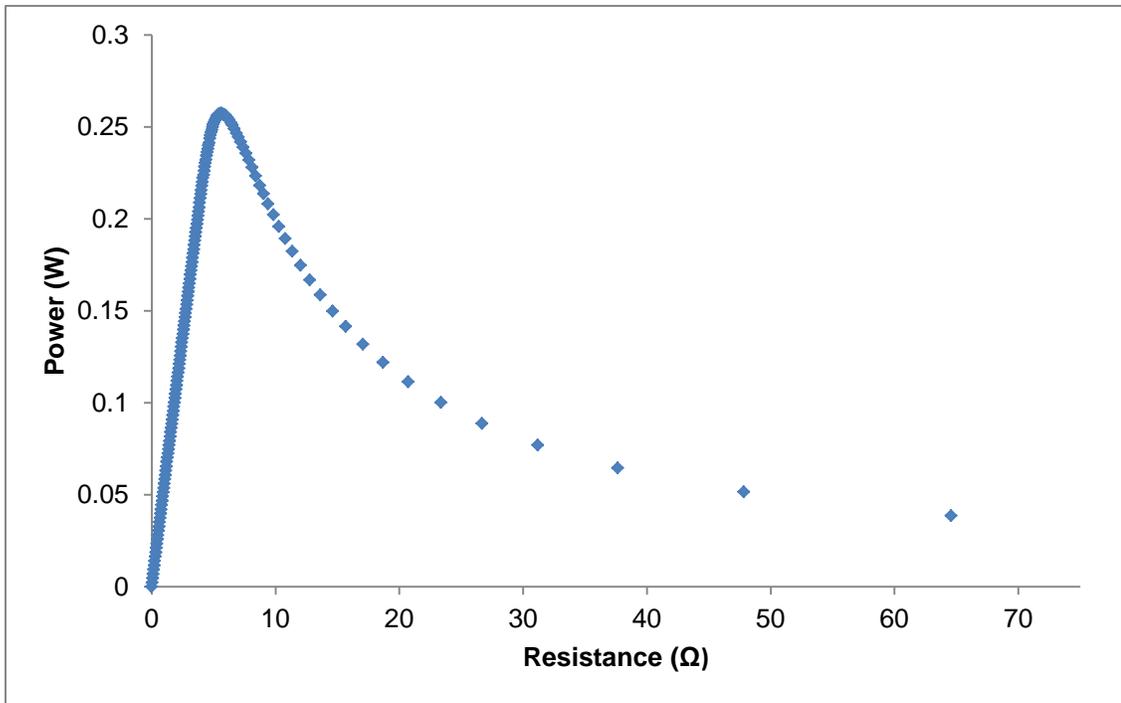


Figure 9: Power curve created using the current and voltage characteristic curve.

## PDMS Testing

To evaluate the viability of PDMS as an encapsulant for a spectral converter, its optical properties were scrutinized. This was accomplished by creating two different thicknesses of PDMS and comparing them to the bare solar cell. The 95% confidence intervals were created from ten sets of data extracted from voltage and current curves.

The PDMS layer decreased short circuit current by 10% regardless of thickness (Figure 10). The PDMS layer also decreased the maximum power output by 8.6% and decreased the open circuit voltage by 1.0% (Figure 11, 12). The fill factor was increased by the PDMS layer (Figure 13). This is because the PDMS affected the short circuit current more than the maximum power output which decreases the bottom half of the ratio. These results agree with an intuitive model suggesting that the bulk of the PDMS does not contribute any loss while the interfaces create nearly all of the attenuation. This could be caused by the high clarity and refractive index of PDMS.

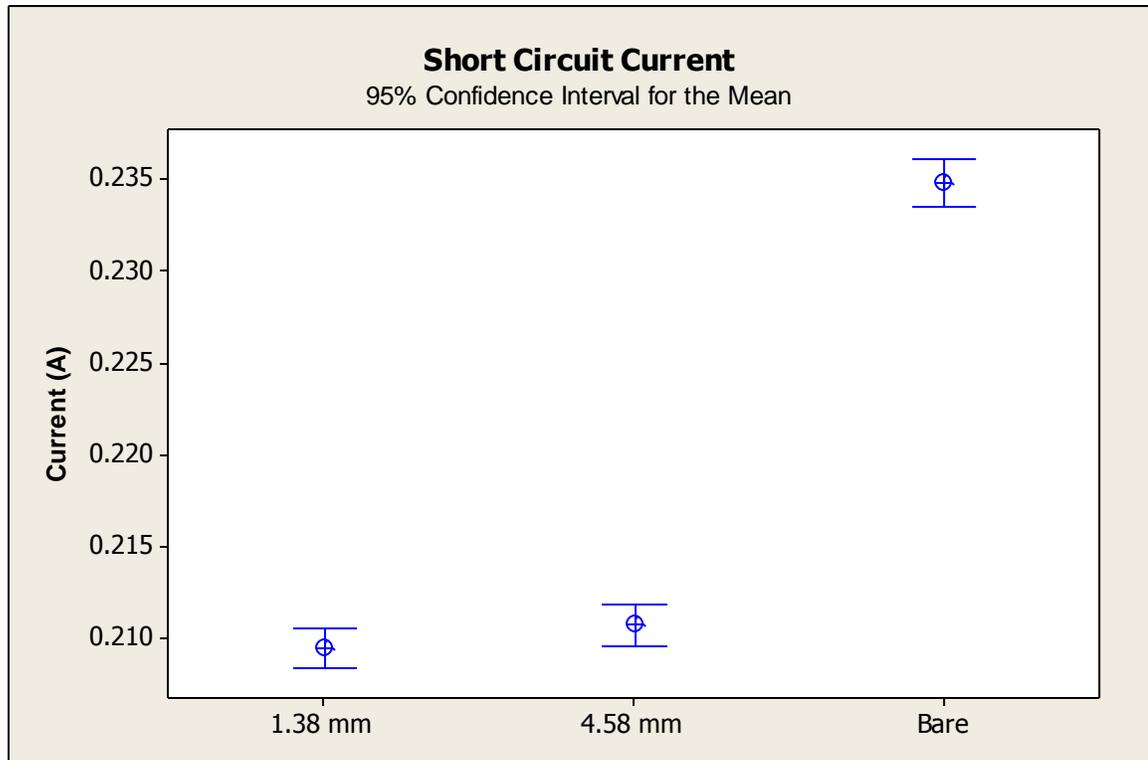


Figure 10: A visible 10% drop in short circuit current due to PDMS with no difference between thickness levels.

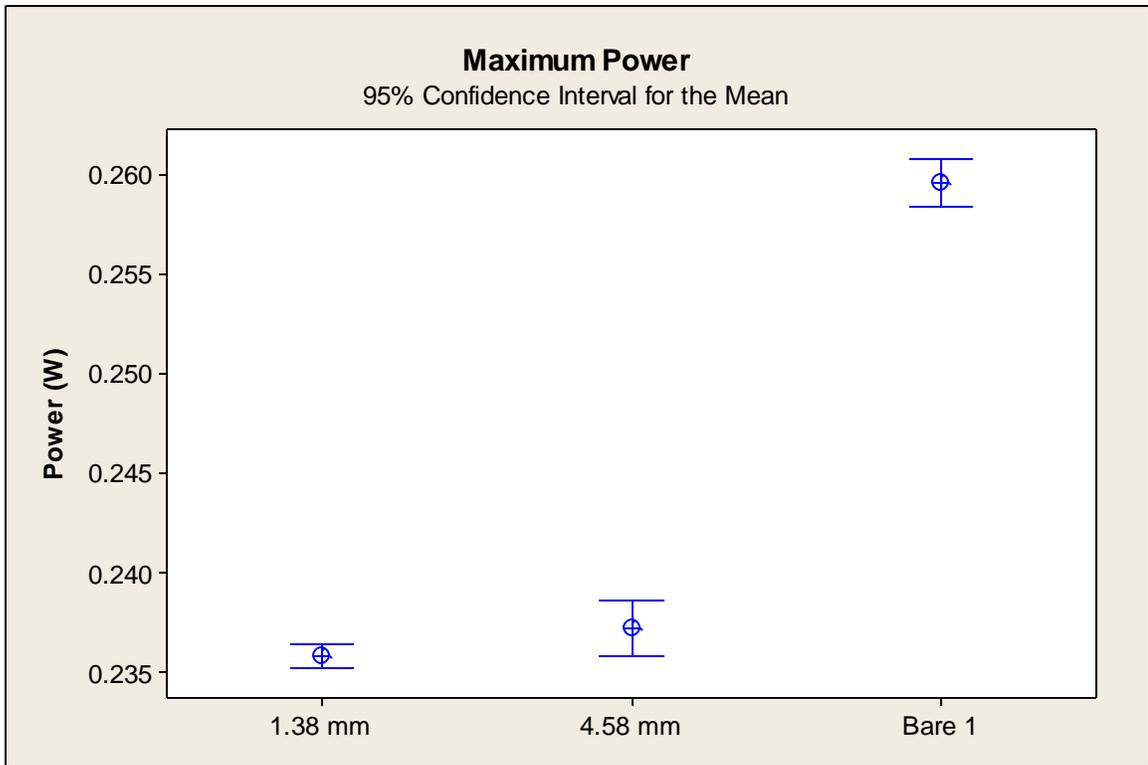


Figure 11: The maximum power output dropped by 8.6% due to PDMS with no differences between thickness levels.

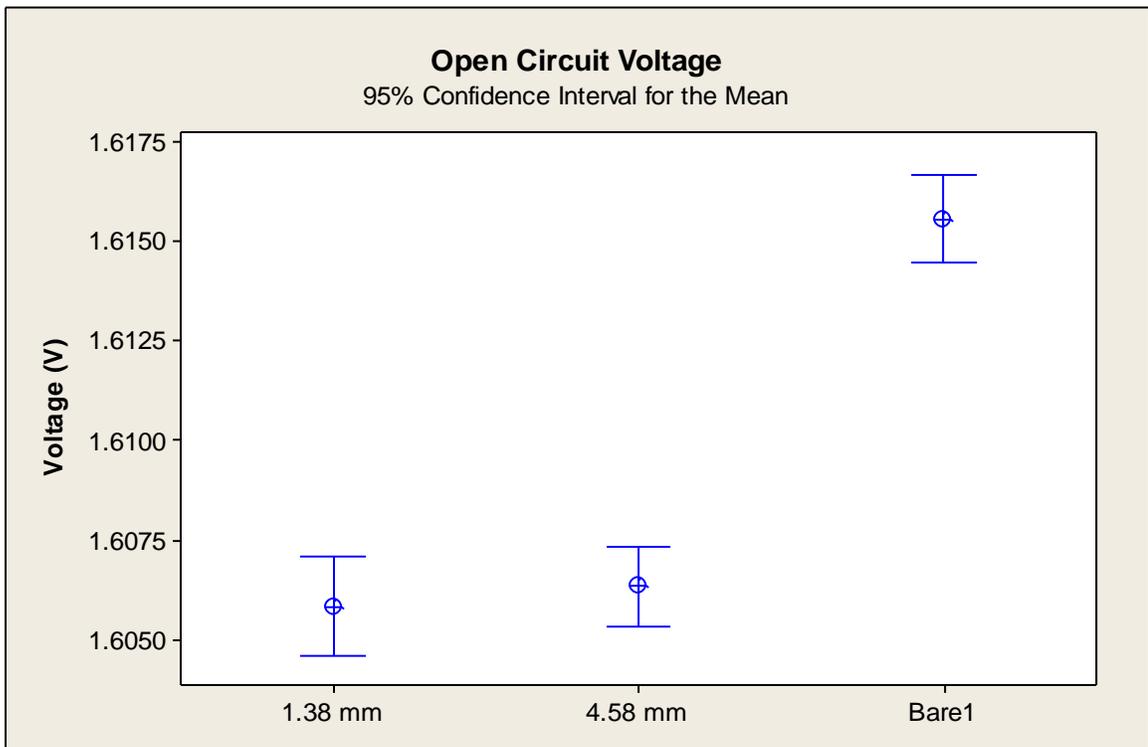


Figure 12: A 1.0% decrease in open circuit voltage confirms a change in illumination rather than a thermal shift.

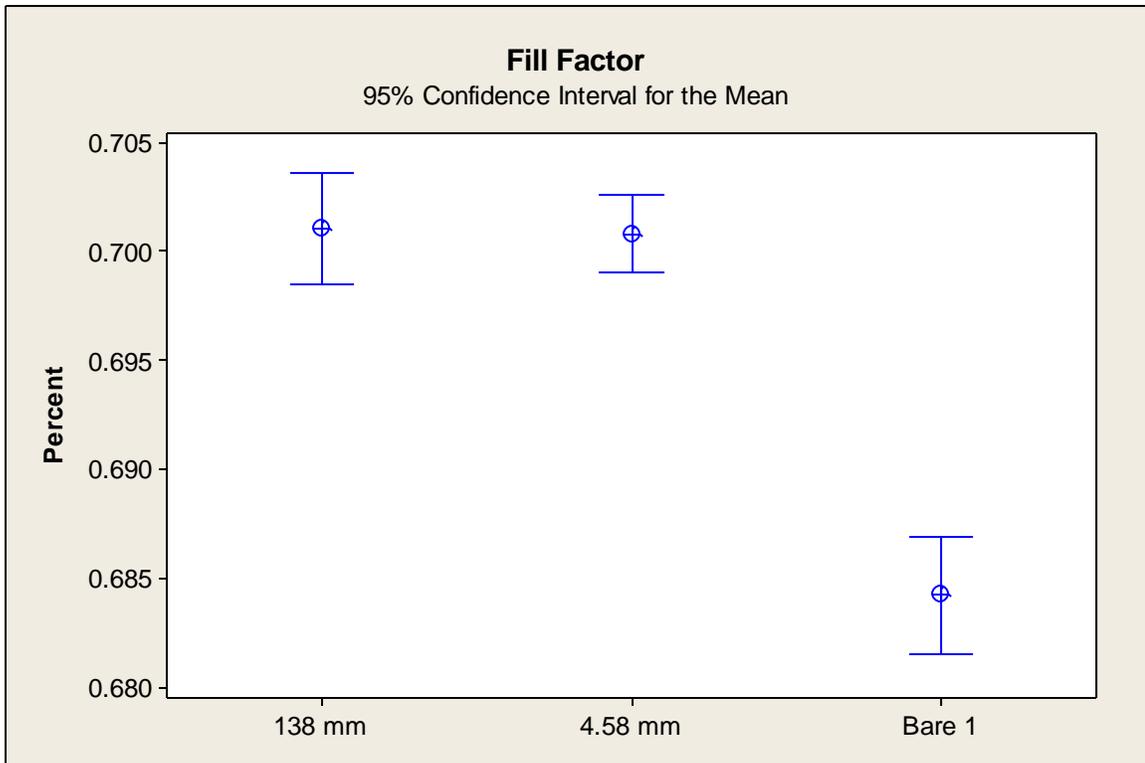


Figure 13: A 2.4% increase in fill factor shows that the maximum power output is affected less than the open circuit voltage or the short circuit current.

## Spectral Converter Testing

The response of the spectral converter was measured against the bare silicon solar cell and a PDMS layer of similar thickness. This allowed for observation of the maximum achievable gain when the spectral converter was compared to the PDMS layer and for the observation of real world efficacy when the spectral converter was compared to the bare solar cell. The spectral converter increased the short circuit current by 1.0% above the bare silicon solar cell (Figure 14). The maximum power output was the same as the bare solar cell, while the PDMS layer decreased maximum power output by 1.0% (Figure 15). In both fill factor and open circuit voltage the spectral converter performed as poorly as the PDMS (Figure 16, 17). Since there were only positive effects on the maximum power output and the short circuit current, while showing no change in open circuit voltage or fill factor, it is possible that the spectral converter was working in some diminished capacity. If the open circuit voltage had decreased, the observed effect could be contributed to an increasing thermal shift.

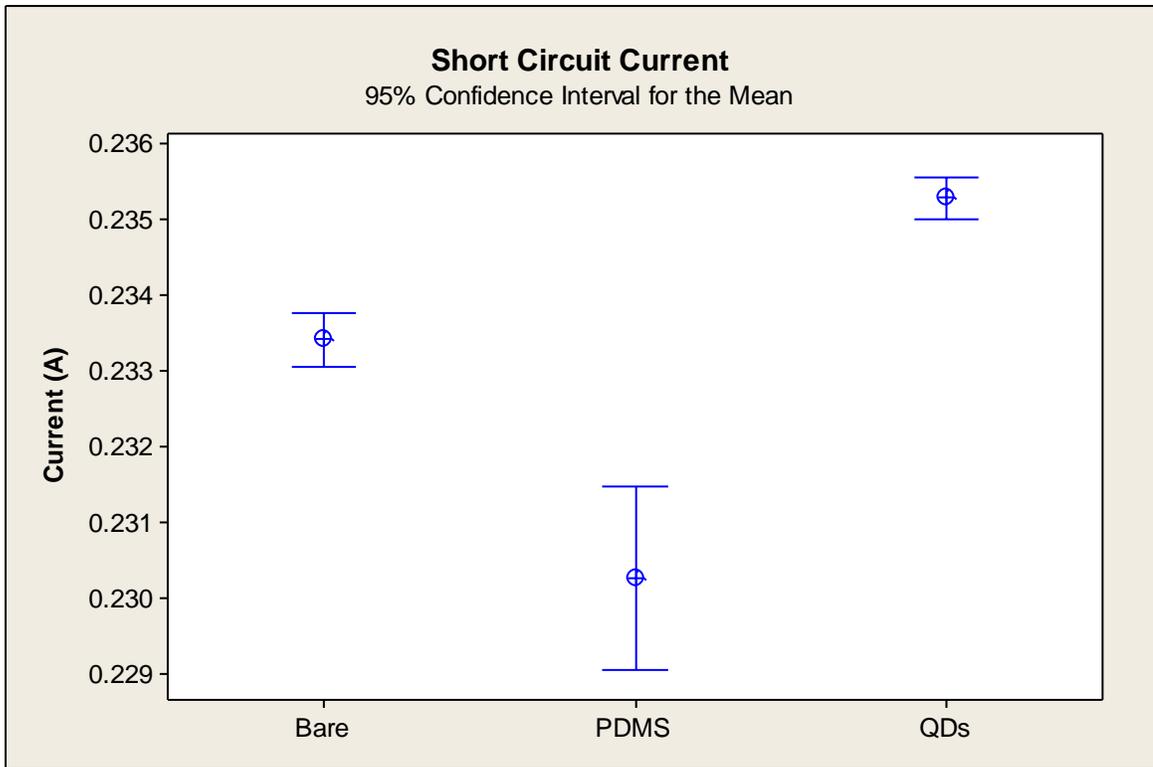


Figure 14: The spectral converter showed a 1.0% increase from the bare solar cell and a 2.2% increase above the PDMS covered solar cell.

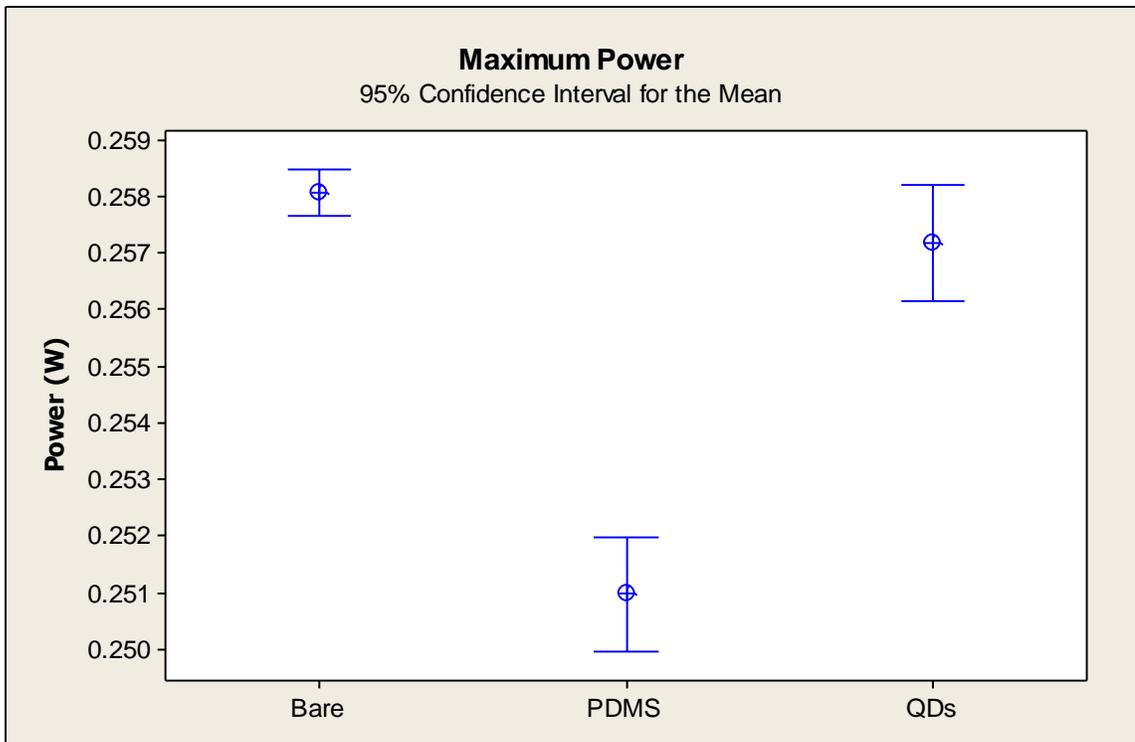


Figure 15: The spectral converter had no effect on the maximum power output but showed a 1.0% increase over PDMS.

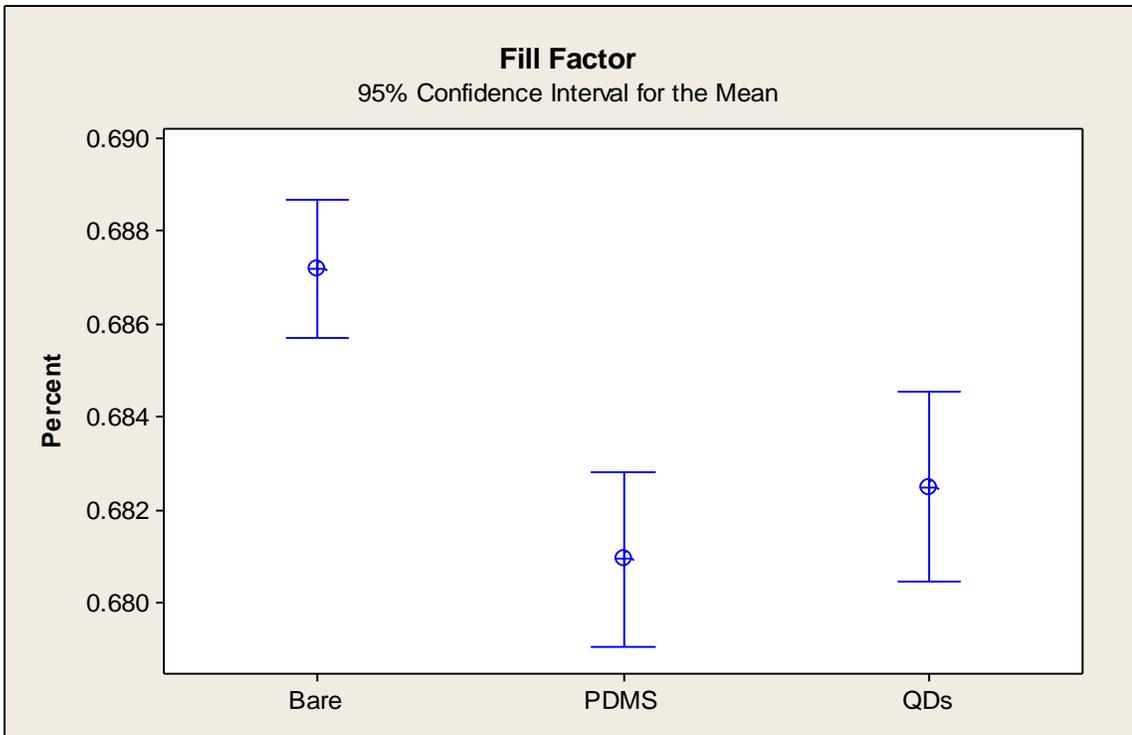


Figure 16: There was no statistical difference between the fill factors produced by the spectral converter and the PDMS.

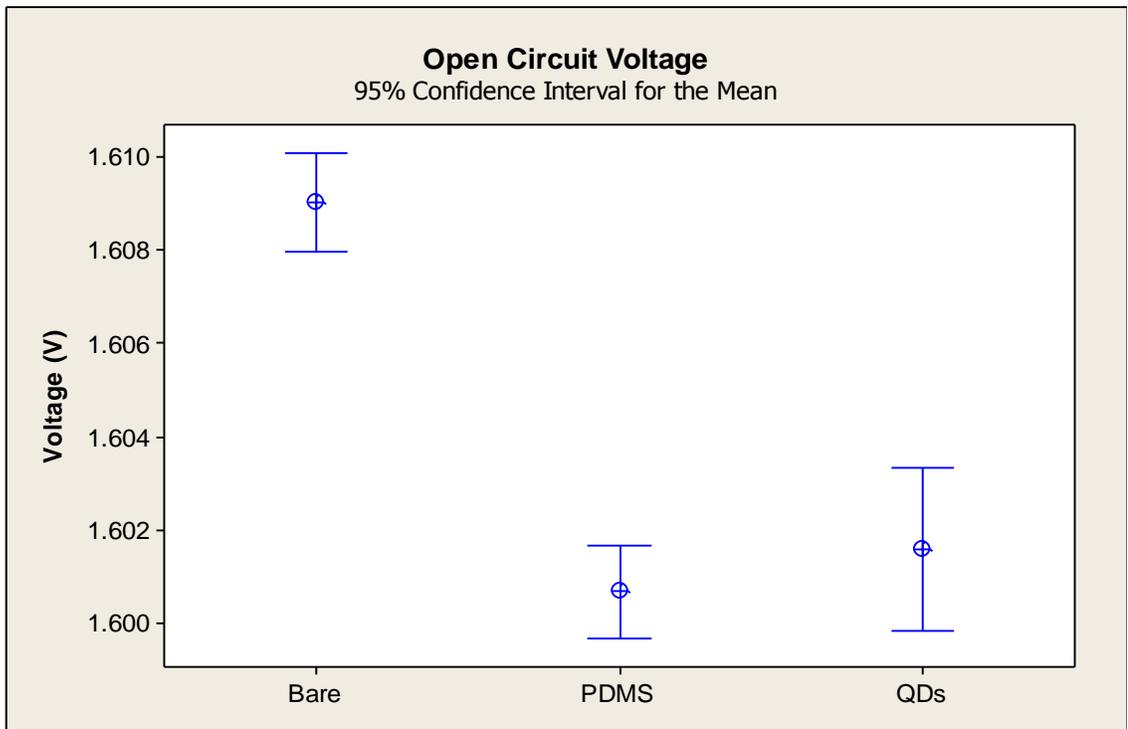


Figure 17: There was no statistical difference between the spectral converter and the PDMS; however both exhibited a decrease in open circuit voltage.

## Discussion

### Interfacial Attenuation

The losses due to the PDMS were inconsistent between the two major experiments. The first experiment showed a loss of approximately 10% in both short circuit current and maximum power output, with smaller decreases in fill factor and open circuit voltage. The second experiment showed losses to short circuit current and maximum power output closer to 1%. Since the second experiment was conducted after the first experiment, there was an improvement in the ability to adhere the PDMS layer to the silicon solar cell simply from practice. All of this suggests that the losses from the interfaces of PDMS and air can be minimized dramatically. Casting PDMS directly onto the surface of silicon solar cells could eliminate an entire interface, decreasing losses by nearly 50%. It is recommended that further studies be conducted by casting each sample on similarly performing solar cells.

### Effect of PDMS Thickness

In all of the experiments, there was no observable difference between the two different thicknesses of PDMS. PDMS is an incredibly transparent material well into the fringes of the electromagnetic spectrum. These results support the use of PDMS as an encapsulant material. It was observed that, while not statistically different, the thicker of the PDMS samples consistently outperformed the thinner sample. It could be the case that the high specific heat and low conductivity of PDMS held the solar cell at a lower temperature during testing, skewing results. It should be noted that these effects were only large enough to warrant consideration for error analysis.

### Optimizing the Spectral Converter

In these trials all quantum dots explored emitted light at the same wavelength. It is possible, if not necessary, to tune the spectral converter based on the efficiency of the quantum dots and the efficiency of the solar cell. A simple energy balance would suffice to determine a range of emission spectra to be tested. Once the emission spectrum is decided, optimizing the

concentration of the quantum dots by minimizing the effect of re-absorbance while still achieving the maximum conversion efficiency should be explored. Finally, since energy production is incredibly cost sensitive, a minimum thickness of quantum dot embedded PDMS should be determined to use as little material as possible to achieve the same effect.

## Conclusions

1. The main source of attenuation in the spectral converter is due to the interface of PDMS and air, which may be minimized by casting the PDMS directly onto the solar cell.
2. Quantum dots are a viable candidate for use in spectral conversion; however, their optimization on a per system basis is required.
3. Due to differences in the emitted spectra of tungsten halogen light sources and the sun the results in this report are a conservative estimate of real world conditions. It would be prudent to create a method of testing using natural light.

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