

## Quantum Dot Technology for Low-Cost Space Power Generation for Smallsats

Theodore G. Stern  
 DR Technologies, Inc.  
 7740 Kenamar Court, San Diego, CA 92020 (858)677-1230  
[tstern@drtechnologies.com](mailto:tstern@drtechnologies.com)

The provision of sufficient power for smallsats is hindered by the lack of collection area and the relatively high cost of efficient photovoltaic conversion. This paper describes the use of quantum dot nanotechnology being developed to improve both performance and cost of space power generation. The development is oriented towards the use of commercially available components and manufacturing technology to satisfy future smallsat space power needs. In the past 20 years, space power generation has evolved from low cost silicon cells to much higher cost gallium arsenide and multi-bandgap cells in order to better overcome the mismatch between the intrinsic bandgaps of photovoltaic converters to the available solar spectrum. The efficiency of conventional photovoltaic converters is also limited by the one-quantum-per-electron conversion process. Quantum Dots can be used to overcome both of these limitations by converting the solar spectrum to a more useful illumination spectrum in order to achieve higher performance from lower cost cells. A Quantum Dot Spectrum Converter can be implemented in a solar cell cover or a luminescent concentrator. Both of these implementations were analyzed for their potential to improve performance, cost and durability.

### INTRODUCTION

Quantum Dots (QD's) are nano-scale semiconductors that have unique fluorescent properties that allow improved efficiency to be approached from spectrum conversion – they can be used to convert the solar spectrum into spectral content that more closely matches the most efficient wavelengths for photovoltaic conversion of a given device. By adjusting the parameters of the quantum dots being produced, including the chosen semiconductor material and the dot size, the absorption and emission spectrum can be tailored to the needs of the photovoltaic converter. An additional phenomenon observed in quantum dots – Multiple Exciton Generation – allows a single high energy (UV-blue) photon to generate multiple low-energy (red) photons. This allows enhanced efficiency by overcoming the inherent so-called “blue loss” of conventional photovoltaics.

This paper describes the results of analysis of two implementations of a Quantum Dot Spectrum Converter (QDSC) – a QDSC Cover and a QDSC Luminescent Concentrator. Implementations of the QDSC in a laminated solar panel, using COTS solar cells and laminating technology usually associated with terrestrial solar PV modules, opens a new approach for smallsats for generating power at a fraction of the cost of conventional space power arrays.

The results of this development have shown the ability to increase the output of conventional silicon,

gallium arsenide and thin film photovoltaic devices using COTS Quantum Dots already in production for biological markers.

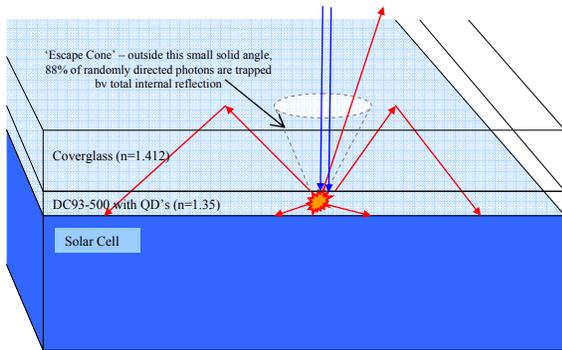
### QDSC IMPLEMENTATIONS

We initially considered a QDSC implementation within a coverglass assembly for use as an add-on component in a conventional solar cell. To more effectively use the 20-50% of the solar spectrum unavailable to today's highest efficiency solar cells, we select quantum dots of particular compositions and sizes to customize the absorption and emission spectra of the QDSC. The primary improvement mechanism is to down-convert unused UV and blue photons into red photons where they generate electron hole pairs in a conventional solar cell with high quantum efficiency.

The phenomenon of Multiple Exciton Generation (MEG) has been observed<sup>1</sup> in QD's, which can result in the photoluminescence of multiple long wavelength (red or infrared) photons for each short wavelength (UV or blue) photon absorbed. This can further enhance solar cell efficiency by allowing use of energy in short wavelength photons that is beyond bandgap. This approach overcomes the fundamental ‘blue-loss’ efficiency limitation associated with conventional single- and multi-bandgap photovoltaic devices. There has also been some evidence that QD's can up-convert IR photons in a multiple photon process<sup>2</sup>, allowing two infra-red photons to be absorbed and yield a usable visible photon. In the future, this may also overcome fundamental ‘red-

loss' limitations, although this phenomenon has not been sufficiently characterized to use in the current development.

For this effort, we analyzed a QDSC implemented within the solar cell coverglass component. The basic function of the QDSC enhanced coverglass is shown in Figure 1, which assumes that the QD's are encapsulated in the adhesive normally used to bond a cover-glass to a solar cell. Incident high energy (blue and UV) photons enter the coverglass and are selectively absorbed by an appropriate concentration of QD's. The emitted photons from photoluminescence of the QD's are subsequently trapped by total internal reflection.

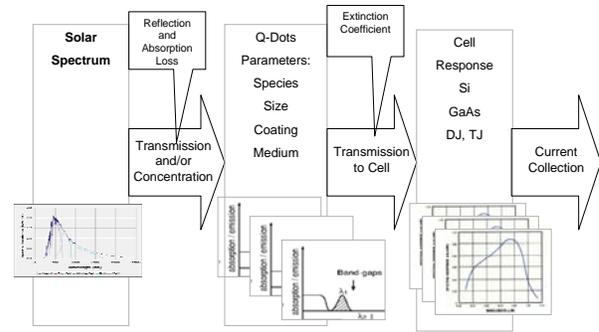


**Figure 1. Basic Operation of the QDSC Cover.**

The random direction of fluorescent emission allows efficient trapping within the glass medium. Since the critical angle  $\theta_c = \sin^{-1}(1/n) = 41^\circ$  for a typical coverglass it can be shown that less than 12% of the re-emitted photons are within the escape cone leading away from the solar cell. The efficacy of this light trapping approach has been shown in prior work on luminescent concentrators<sup>3</sup>.

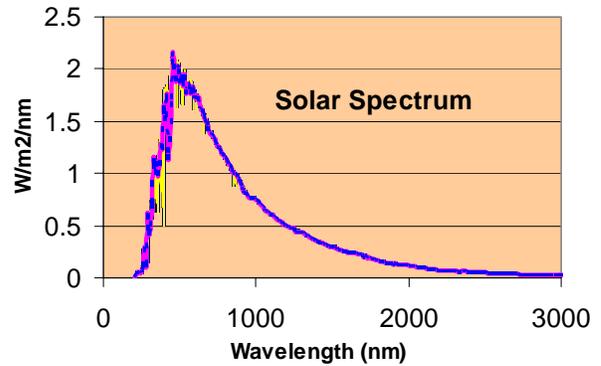
### Modeling of the QDSC

We created detailed and representative models of each component in a QDSC enhanced solar array. The approach we used is a spreadsheet-based numerical analysis using closed form and Monte Carlo techniques to simulate the response and spectra of photons, starting with the solar spectrum, and ending up with the solar cell spectral response. For each reflection, absorption, or spectral response function, a detailed spline model was developed to analyze the effect of each component in the efficiency chain, as shown in Figure 2.



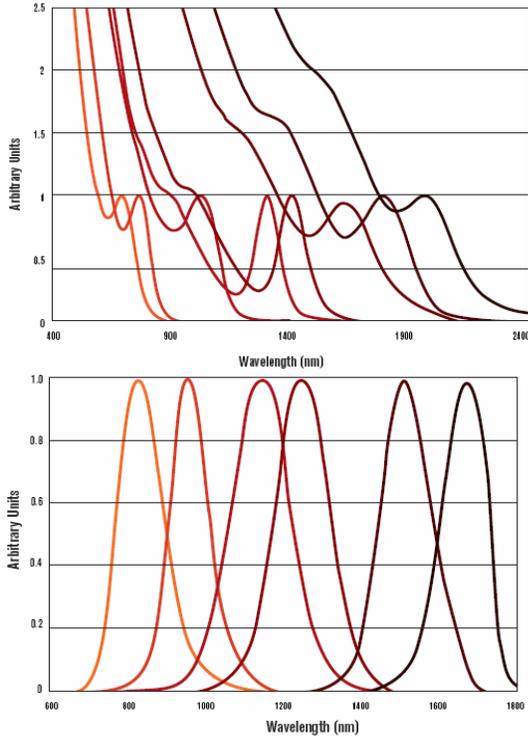
**Figure 2. Modeling Approach for Quantum Dot Enhanced Photovoltaics.**

The solar spectrum was modeled discretely using publicly available data from NASA solar observatories and “Living with a Star” data, starting with the flux content at discrete spectral intervals, and integrating these data to create energy content for a set of 250 discrete spectral bands from 200nm to 4800nm. This provides good spectral resolution as shown in Fig. 3.

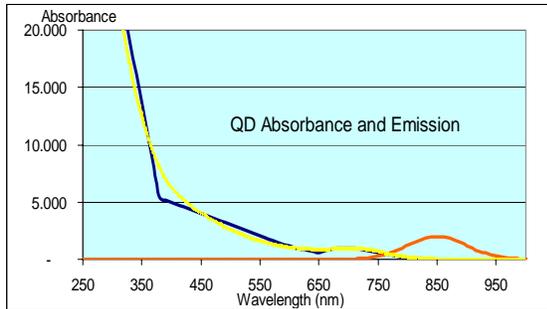


**Figure 3. Solar Spectrum Modeled With 250 Discrete Bands**

Using the spectral properties data from commercial quantum dot suppliers, including measured spectral absorption and emission of various types and sizes of QD's (Fig. 4), we developed a spline model for absorbance, as shown in Fig. 5. This provides the absorbance as a function of the molar concentration of QD's, which, by Beer's law, predicts the absorption for a given thickness of QD-doped material. Note that in all cases, absorbance is given in arbitrary units.

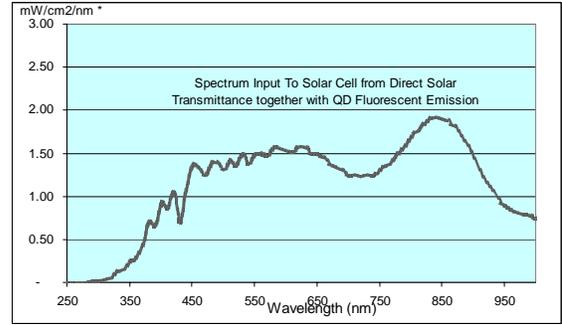


**Figure 4. Absorbance and Fluorescent Emission of Several Types of PbS Quantum Dots.**



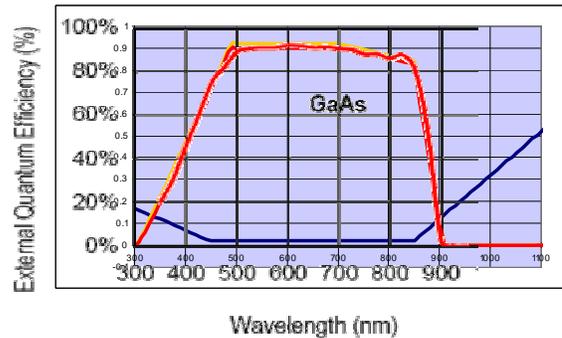
**Figure 5. Spline Model of the PbS Quantum Dot Absorbance Compared to Measured Data.**

Once the absorbance and photoluminescence functions were modeled for the QDSC layer, we applied those functions to the input solar spectrum to provide a spectrum of light illuminating the target solar cell. This comprises the sum of the transmitted solar energy (i.e. not absorbed by the QDSC), and the absorbed and fluoresced energy of the quantum dots in the QDSC, as shown in Fig. 6. This part of the model also accounts for the quantum yield of the QD's and the photoluminescence lost out the front side of the coverglass from incomplete light trapping.



**Figure 6. Solar Cell Input from Transmittance and Fluorescence in the QDSC Layer.**

Using vendor data for the spectral response of the solar cell, we created a spline model for solar cell reflection and internal quantum efficiency to provide a closely modeled spectral response, as shown in Fig. 7. When applied to the spectrum provided to the solar cell, a solar cell output response to the spectrum is calculated, again for each discrete spectral band, and the resulting light generated current indicates the potential for improved efficiency from QDSC-enhanced photovoltaics.



**Figure 7. Spectral Response Data Overlaid on Spline Model of Solar Cell Quantum Efficiency.**

### *QDSC Cover Performance Trades*

The model was used to develop projections for the performance of the QDSC coverglass for various crystalline and thin film photovoltaic options using QD's of different species and spectral properties. For each combination of solar cell and quantum dot, a parametric analysis was performed to determine the performance in the coverglass configuration as a function of QD Absorbance, Quantum Yield (with and without Multiple Exciton Generation, or MEG), and most importantly, the QD's characteristic emission wavelength and spectral absorbance.

Figure 8 shows some a typical result of this parametric analysis for a Single Junction (SJ) GaAs solar cell, for the case where MEG by high energy

(UV) photons is included. In this parametric analysis, we considered the potential for using quantum dots with various characteristic emission wavelengths, a parameter which can be adjusted through the achievement of a specific distribution of QD sizes. Although we considered the possible emission wavelengths from 400nm through the characteristic band-edge wavelength of the associated photovoltaic device, in practice, the various kinds of quantum dots have limited wavelength ranges to choose from. In particular, PbS QD's tend to be manufacturable only with photo-emission wavelengths  $> 750\text{nm}$ , while CdSe QD's tend to be shorter wavelength emitters  $< 700\text{nm}$ . This is significant in the model because the PbS system has a different absorption characteristic, with higher separation between the characteristic emission and absorption bands.

In these parametric analysis results, we observe a dual mode optimum for the emission wavelength resulting in the best efficiency enhancement. The two modes are associated with the peak in the solar spectrum, i.e. 550nm and the solar cell inherent bandgap wavelength, i.e. 873nm for SJ GaAs; the QDSC optimum emission wavelength for high absorbance is seen at shorter wavelengths while the low absorbance QDSC optimizes at an emission wavelength near the solar cell bandgap edge.

We hypothesize that this is because the solar intensity falls off sharply at wavelengths longer than 550nm, so the spectral conversion has significantly lower benefit compared to the losses incurred from absorption near the first exciton characteristic peak wavelength. For longer wavelength emitters, low absorbance is needed to allow as much of the spectrum near the PV cell bandgap to transmit unimpeded while benefiting only from the high UV absorbance.

This analysis was repeated for several different PV cell types; in each case a parametric analysis was done as a function of the characteristic emission wavelength of the QD's and the absorbance, or optical density of the QD-composite coverglass. For the case of multi-bandgap solar cells, only the response of the highest bandgap solar layer was analyzed with short wavelength QD emission, because a longer wavelength emitter would absorb too much of the blue energy needed to achieve high efficiency in a multi-bandgap cell. The results are shown in Table 1 for the case where no MEG is assumed, and Table 2, which includes consideration of MEG. In both cases, we show significant improvements in light generated current, which translates directly into efficiency improvements, with both single-bandgap and multi-bandgap solar cells.

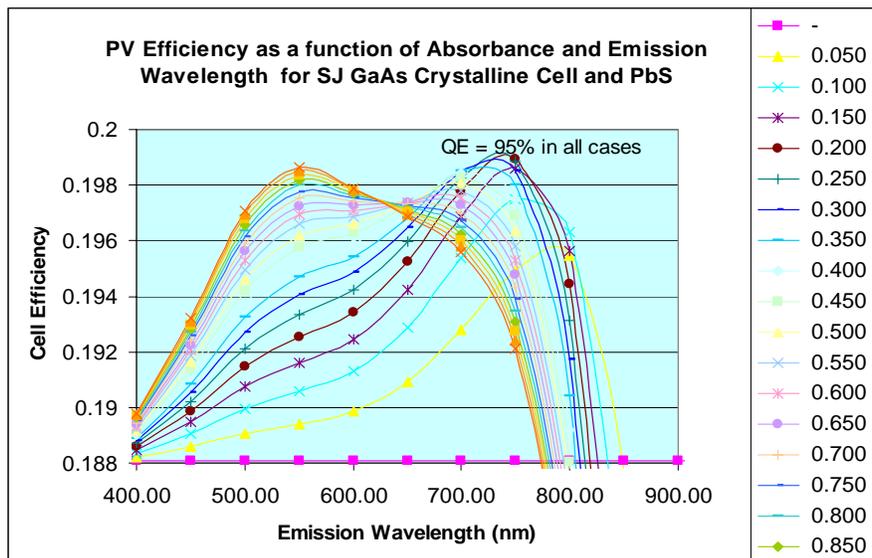


Figure 8. Parametric Analysis Result for Single Junction GaAs Solar Cell using PbS QD's.

**Table 1. QDSC Coverglass Efficiency Enhancements Optimized for Each PV Cell Type, Assuming No MEG.**

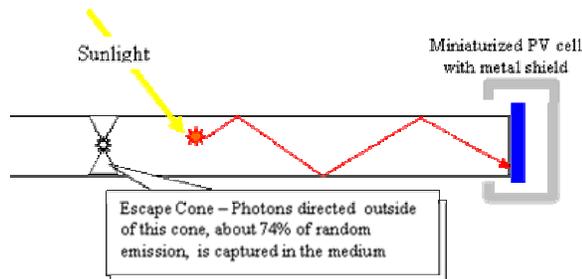
Without MEG					
Solar Cell	Bandgap	QD Type	Characteristic Wavelengths (nm)		Efficiency Enhancement
			QD Emission	First Absorption Pk	
Silicon	1.12	PbS	800	650	8.2%
GaAs	1.42	PbS	800	650	5.4%
GaAs	1.42	CdTe-CdS	500	490	4.2%
InGaAsP	1.8	CdTe-CdS	500	490	7.4%
CIGS	1.08	CdTe-CdS	550	540	7.0%
a-Si	2.76	CdTe-CdS	440	430	2.2%

**Table 2. QDSC Coverglass Efficiency Enhancements Optimized for Each PV Cell Type, Assuming MEG.**

With MEG					
Solar Cell	Bandgap	QD Type	Characteristic Wavelengths (nm)		Current Enhancement
			QD Emission	First Absorption Pk	
Silicon	1.12	PbS	800	650	10.0%
GaAs	1.42	PbS	800	650	6.0%
GaAs	1.42	CdTe-CdS	500	490	6.0%
InGaAsP	1.8	CdTe-CdS	500	490	7.5%
CIGS	1.08	CdTe-CdS	550	540	8.5%
a-Si	2.76	CdTe-CdS	440	430	2.3%

**QDSC Luminescent Concentrator Trades**

The random direction of re-radiation also enables the application of QD fluorescence in a non-tracking concentrator approach. The approach of trapping the re-emitted photons within an optically dense slab by total internal reflection – sometimes known as a luminescent concentrator – is shown in Figure 9. In a well polished slab of glass (or, as an alternative, silicone coated glass or replicated silicone layer), with an index of refraction of >1.4 over 74% of re-emitted energy will be trapped in the denser medium and reflected with near perfect reflection efficiency until it reaches an orthogonal edge. Solar cells placed at the edge receive this light energy at the emission wavelength.

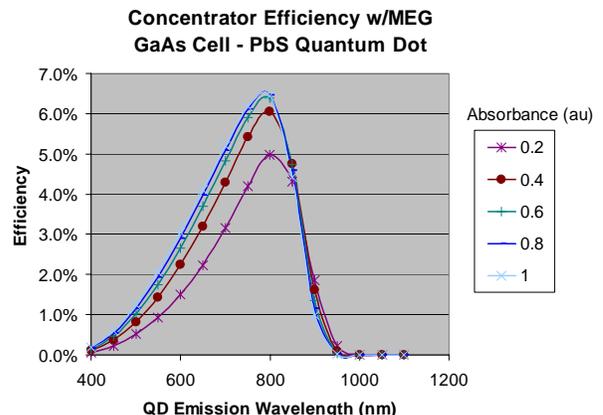


**Figure 9. QDSC Luminescent Concentrator**

We performed an analysis of the concentrator configuration using the same basic approach as for

the QDSC Cover. We used the ability to control the characteristic emission of the quantum dot as a primary trade-off parameter. Other variables used as parameters in the study included the concentration ratio, QD quantum yield and absorbance in the QD composite medium as another.

A typical result for a GaAs solar cell in the QDSC Luminescent Concentrator is shown in Fig. 10. For this parametric analysis we used a geometric concentration of 10, controlling the thickness of the QD-composite concentrator slab and surrounding its entire perimeter edge thickness with solar cells. We also assumed a quantum yield of 95% with an additional MEG yield of 60%.



**Figure 10. Concentrator Efficiency at a CR Of 10**

The results show an optimum emission frequency for the QD is near the solar cell bandgap. The choice of a long wavelength emitter also provides the greatest opportunity for MEG by driving the UV part of the solar spectrum to higher multiples of  $E_g$ , the characteristics bandgap of the QD. Under these conditions, a system efficiency of >6% is projected.

Even though 6% efficiency doesn't appear to be competitive at first, several factors serve to provide a significant benefit for this configuration. With a geometrical concentration of 10, the total solar cell cost is significantly reduced, even considering the lower system efficiency obtained. The QD-composite can have a very low mass compared to a mounted, shielded solar cell, so that total mass of an array will be reduced. Under end-of-life conditions, the temperature and radiation shielding control provided by a concentrator configuration could result in a much more favorable comparison against the figures of merit, Watts/kilogram and \$/Watt, for a conventional planar array.

## CONCLUSIONS

We developed an analytical model that can be used to predict the performance of various QDSC implementations and configurations. The analytical model shows that the performance of a variety of solar cells can be enhanced using a Quantum Dot Spectrum Converter incorporated into the cell coverglass. The ability to customize emission wavelength, and to take advantage of MEG, results in an improvement in the effective utilization of the UV and blue regions of the solar spectrum. For matching to single bandgap solar cells which typically have lower bandgap values, the QDSC used for optimum enhancement can either take the form of a high

optical density layer with short emission wavelength or a lower optical density layer with long emission wavelength; both enhance the cell's light generated current to approximately the same level. For the best combinations of solar cells and QD's, light generated current and corresponding photovoltaic efficiency can be enhanced up to 10% if high QD quantum yield can be achieved.

Use of a QDSC in a concentrator configuration also shows promise for low-cost and high performance. With a concentration of 10, a QD luminescent concentrator can achieve an efficiency of >6%, and shows the possibility of achieving lower mass and cost if high quantum yield, durable quantum dots can be configured into a suitable medium.

## ACKNOWLEDGMENTS

This work was sponsored in part by the NASA Glenn Research Center under a Small Business Innovation Research program, contract NNC06CA64C. The author would also like to thank Sheila Bailey and Mike Piszczor of the NASA Glenn Research Center, Stephanie Castro of the Ohio Aerospace Institute, and Margaret Hines of Evident Technologies for their technical guidance and support.

## REFERENCES

- <sup>1</sup>Ellingson, R.J, et al, "Highly Efficient Multiple Exciton Generation in Colloidal PbSe and PbS Quantum Dots," *Nano Letters* 5:5, March, 2005
- <sup>2</sup>Barnham, K. et al, "Quantum-Dot Concentrator and Thermodynamic Model for the Global Redshift," *Applied Physics Letters* 76:9, February, 2000
- <sup>3</sup>Rapp, C., Boling, I., et al, "Determination of the Technical Feasibility of Fluorescent Concentrators," Final Report, SAND79-7005, March, 1979