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EVALUATION DU POTENTIEL DE CONCENTRATEURS A QUANTUM DOTS POUR LA PRODUCTION D'ELECTRICITE PHOTOVOLTAÏQUE

Rapport final

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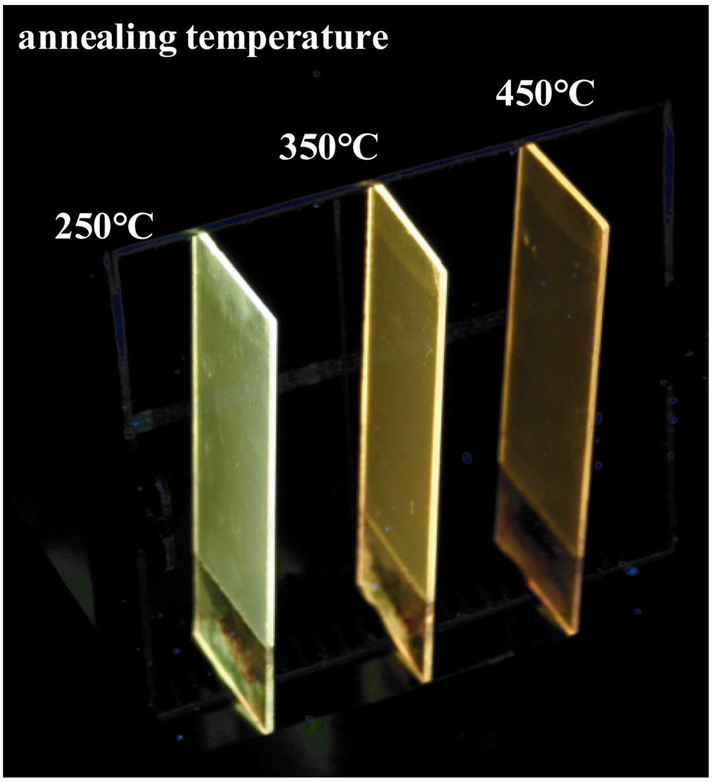

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Contents

Abstract

One of the most promising application of semiconductor nanostructures in the field of photovoltaics might be planar photoluminescent concentrators. Even for diffuse solar radiation considerable concentration factors might be achieved. Such devices have originally been designed on the basis of organic dyes and might benefit from a considerably improved lifetime when replacing the organic fluorescent substances by inorganic semiconductor nanocrystals, so-called quantum dots.

Quantum dot containing nanocomposite thin films are synthesized at EPFL-LESO by a low cost sol-gel process. In order to study the potential of the use of quantum dot solar concentrators in photovoltaic solar energy conversion, reliable computer simulations are needed.

A tool for ray tracing simulations of quantum dot solar concentrators has been developed at EPFL-LESO on the basis of Monte-Carlo methods that are applied to polarization-dependent reflection/transmission at interfaces, photon absorption by the semiconductor nanocrystals and photoluminescent reemission.

Together with the knowledge on the optoelectronical properties of suitable photovoltaic cells, such simulations allow to predict the total efficiency of the envisaged concentrating PV systems, and to optimize pane dimensions, photoluminescent emission frequencies, and choice of PV cell types.

1. Introduction to the concept and initial state of the art

One of the most promising applications of semiconductor nanocrystals in the field of photovoltaics might be planar photoluminescent concentrators. Even for diffuse solar radiation considerable concentration factors can be achieved. Typical concentration factors for Compound Parabolic Concentrators (CPCs based on parabolic mirrors) are in the order of 2 [12], while for fluorescent planar solar concentrators typical concentration factors above 30 have been predicted [5]. Such devices have originally been designed on the basis of organic dyes [8], and will benefit from a considerably improved lifetime when replacing the organic fluorescent substances by inorganic semiconductor nanocrystals, so-called quantum dots [4,7]. Additionally, the tunability of the optical properties by the size of the nanocrystals provides a large amount freedom for the design and optimization of such devices.

A schematic drawing of the principle of fluorescent solar concentrators proposed by Goetzberger is shown in Fig.1(a). One or several waveguides are fabricated from panes of transparent media doped with fluorescent dyes. Incoming solar radiation is absorbed in the volume of the waveguides, and isotropically reemitted by fluorescence. A large part of the emitted radiation is captured by total internal reflection and propagates to the edges. The likewise concentrated radiation is converted by photovoltaic cells with band gaps matching the wavelengths of the spectral emission lines of the photoluminescent materials. By choosing dyes with suitable absorption and emission properties, stacks of fluorescent collectors can be designed, with absorption edges chosen in a manner similar to multi-junction photovoltaic cells. Due to this step-like absorption edge/band-gap matching, the conversion efficiency can be higher than for single-junction devices.

The same geometry has been used in quantum dot solar concentrators [4,7], where photoluminescent semiconductor nanocrystals replace the fluorescent dyes. Instead of immersing quantum dots in transparent resins, we propose to deposit quantum dot containing silicon dioxide films on highly transparent low iron glass substrates by sol-gel dip-coating. If the refractive index of the coating is close to the one of the substrate, internal reflection occurs mainly at the surface of the coating, as depicted in Fig1(b). For clarity, the thickness of the coating is exaggerated in the representation.

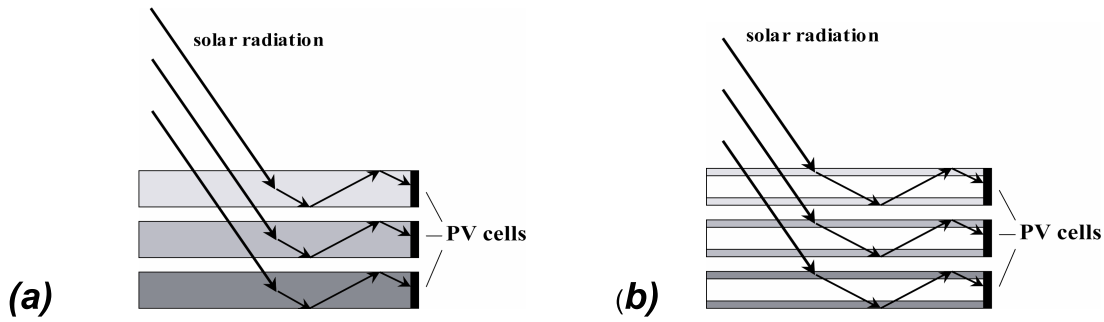


Fig.1: *Quantum dots immersed in bulk of panes (a), and contained within a coating applied to the glass.*

Fig.2 shows a photograph of CdS nanocrystal containing SiO_2 coatings produced by low-cost sol-gel dip-coating at EPFL-LESO [1]. The samples were annealed at 250°C, 350°C, and 450°C. The strong emission from the edges of the samples is due to the concentration of the photoluminescent radiation in the waveguides by total internal reflection. The obtained colors of the visible photoluminescence, ranging from green for 250°C to yellow for 350°C and orange for 450°C, illustrate the effects of quantum confinement. The size distribution of the nanocrystals depends on the annealing temperature during the self-organized crystal growth. The three-dimensional quantum confinement in the quantum dots induces a discretization of electronic states, very much like in atoms or molecules. The resulting optical properties depend on the crystal size and can thus be tuned by varying the dimensions of the nanocrystals (and thus by varying the annealing temperature). Important parameters are the internal quantum yield (number of photons emitted from nanocrystal divided by the number of photons absorbed by the nanocrystal), and the external quantum yield (number of photons arriving at PV cell surface divided by the number of photons taken up by the concentrator). The photovoltaic concentration of a single fluorescent pane can be defined as the ratio of the electrical power produced by the cell when being illuminated with the concentrated radiation and the electrical power produced by the cell when being illuminated with the AM1.5 global spectrum.

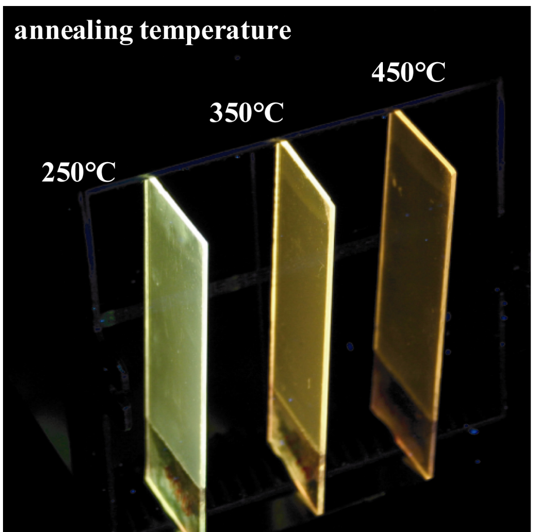


Fig.2: *Photograph of SiO_2:CdS samples formed at 250°C, 350°C, and 450°C [1].*

2. Project Goals

The principal goal of the project is to evaluate the feasibility and the potential of photoluminescent quantum dot solar concentrators for photovoltaic electricity production. The optical properties of the fluorescent semiconductor nanocrystals shall be measured and used in Monte-Carlo simulations in order to predict the energy conversion efficiency of the envisaged devices.

Advantages of the concept of photoluminescent quantum dot solar concentrators :

- planar fluorescent concentrators might become highly competitive with respect to cost efficiency (price of kWh), especially if the quantum dots can be applied as coating
- the fluorescent concentrator is the only known concept allowing to concentrate considerably both direct and diffuse solar radiation
- the recent development of highly fluorescent quantum dots by nanotechnology can be exploited in order to create highly durable flurescent planar solar concentrators instead of devices based on instable organic fluorescent dyes
- the PV cells will be exposed to spectrally matched radiation, thereby avoiding the efficiency loss due to excessive heating in conventional concentrators
- application possible as photovoltaic windows (PV cells located on the edges of the glass pane),
- perfect architectural integration of the novel devices into facade glazing (opaque and translucent parts)

Based on the simulated system efficiencies, it shall be judged whether the concept of quantum dot solar concentrator merits further development.

3. Approach

- **Completing the Monte-Carlo ray tracing software for simulation of quantum dot solar concentrators**
  improve input/output facilities of program, and include polarization dependence of reflection/transmission at interfaces

- **Establishing reliable methods for the determination of the optical constants of the photoluminescent materials**
  most important parameters: absorption coefficient α, spectra of photoluminescent emission, define optical measurements to be taken, establish/modify the experimental setups necessary for the measurements, develop algorithms for analysis of optical data

- **Validation of the simulation software**
  comparison simulations vs. theoretical formulae, comparison simulations vs. measurements

- **Provide data of optical constants for quantum dots**
  measurement of VIS-emitting colloidal quantum dots in solution, extrapolation for IR-emitting quantum dots

- **Simulation of quantum dot solar concentrators**

    - quantum dots in bulk (immersed in volume of pane)
    - quantum dots applied as coatings
    - variation of concentrator dimensions
    - variation of concentration of quantum dots
    - predict system efficiencies and quantity of electrical power produced

4. Results

Completing the Monte-Carlo ray tracing software for simulation of quantum dot solar concentrators

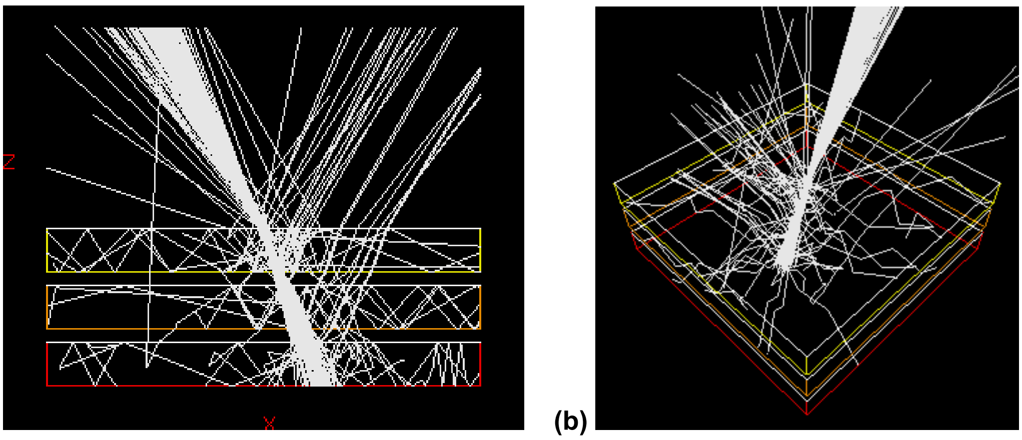
For a more detailed description of our computer code “PhotonSim” please see publications [2] and [3].

Improvement of input/output facilities of program:

Several MATLAB routines have been written to facilitate parameter studies by performing series of simulations. The program can now be started from MATLAB routines, and the results saved by the program can be evaluated automatically.

Taking into account light polarization:

The polarization dependence of the reflection/transmission at interfaces has been taken into account (initially the program worked with average polarization). At each interface the full ellipsometric calculus is performed, and the shape and orientation of the polarization ellipsis is stored for the next reflection/transmission. Fig. illustrates the three-dimensional photon trajectories in a triple stack concentrator.



(a) (b)

Fig. 3: *Visualization of three-dimensional photon trajectories in a triple stack concentrator.*

Establishing reliable methods for the determination of the optical constants of the photoluminescent materials

The knowledge on the absorption coefficient is highly important to estimate the reabsorption of the concentrated light by the material itself. In order to obtain high precision in a large spectral range, solutions of colloidal quantum dots are measured in different concentrations. The measurements of performed in normal transmission using a special quartz or glass cuvette with fine walls. The influence of the multiple reflections due to the cuvette walls are taken into account by the data analysis. For this purpose, a MATLAB routine has been written, yielding the absorption coefficient α of the material.

The spectra of photoluminescent emission depend in general on the excitation energy. For a complete experimental characterization of fluorescent quantum dots, a monochromator is used for the selection of the excitation energy, and a spectrophotometer to acquire the emission spectra. An example is shown in Fig. 4. The sample consists of red light emitting colloidal CdSe/ZnO core shell quantum dots with a crystal size of approx. 5 nm (Evident Technologies). The displayed spectra have been measured with a spectral resolution of 5 nm FWHM, the bandwidth of excitation was 7 nm FWHM. A clear dependence of the emission spectra on the excitation energy is revealed. The likewise measured fluorescence maps are imported into the simulation program, which uses the inverse function method to generate random emission events according to the corresponding emission probabilities.

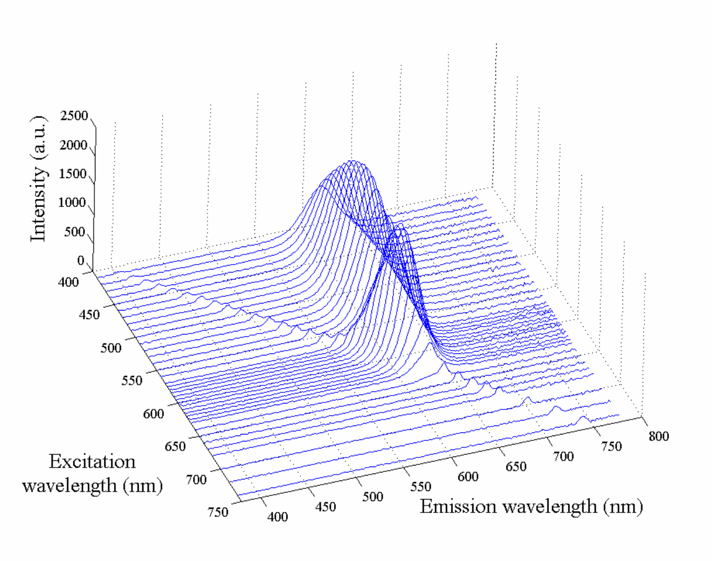


Fig. 4: *Photoluminescence spectra as a function of excitation energy for red light emitting CdSe/ZnO core shell quantum dots, crystal size 5 nm.*

Validation of the simulation software

Comparison Simulation vs. Theory :

The transmission and reflection events at the interface are generated from the Fresnel formulae by a Monte Carlo algorithm based on the inverse function method. A verification of the computer code is shown in Fig. 5. The solid lines correspond to the theoretical transsmittance/reflectance values for elliptically polarized rays with $\psi = 35°$ and $\alpha = 30°$ incident at the interface of two media with the refractive indices 1.5 and 1. The simulated data (open circles in Fig.5) match perfectly the theoretical curves. Above the critical angle, total reflection occurs.

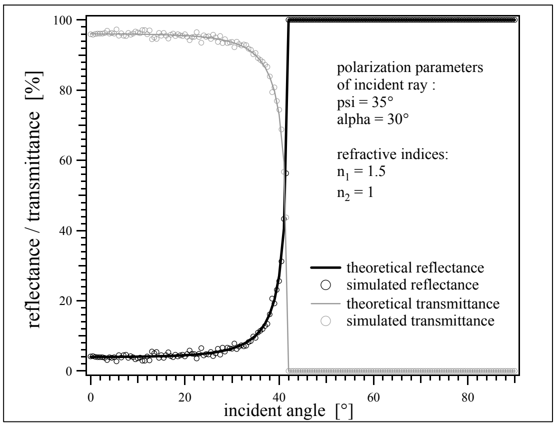


Fig. 5: *Validation of transmission/reflection probabilities for elliptically polarized rays. The simulated data match the theoretical curves.*

Comparison Simulation vs. Experiment:

For fluorescent dye colored PMMA samples, spectra of edge emission were measured and simulated. The length of the mean lateral optical path was varied. Simulations and measurements showed very good agreement. For colloidal CdSe/ZnS quantum dots, transmittance spectra have been simulated and compared to the experimental data. For the transmittance measurement, the core shell quantum dots were immersed in toluene and contained in a glass cuvette with an optical path length of 10 mm. The results for blue emitting CdSe/ZnS quantum dots with a crystal size of 2 nm are illustrated by Fig. 6. A close match between simulated and measured transmittance data has been achieved.

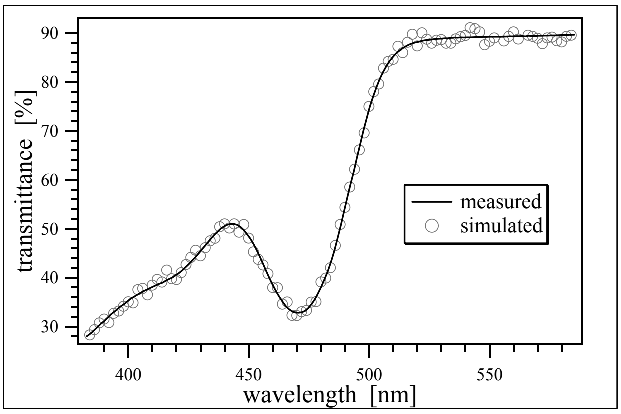


Fig. 6: *Measured and simulated transmittance, blue emitting CdSe/ZnS quantum dots, crystal size 2 nm.*

Provide data of optical constants for quantum dots

Commercially available VIS-emitting CdSe/ZnS quantum dots with four different emission wavelengths (corresponding to the colors blue, green, yellow and red) have been characterized experimentally by determining the absorption coefficient and the fluorescent map.

Since NIR-emitting quantum dots were not easily available without special agreements (e.g. PbS quantum dots from EVIDENT Technologies), the optical data had to be extrapolated. The extrapolation procedure is illustrated by Fig.7. For the simulations, various Stokes shifts from 25nm to 85nm have been assumed (For comparison: the Stokes shift of CdS quantum dots immersed in SiO_2 coatings produced by our laboratory exhibit Stokes shifts in the order of 60nm.

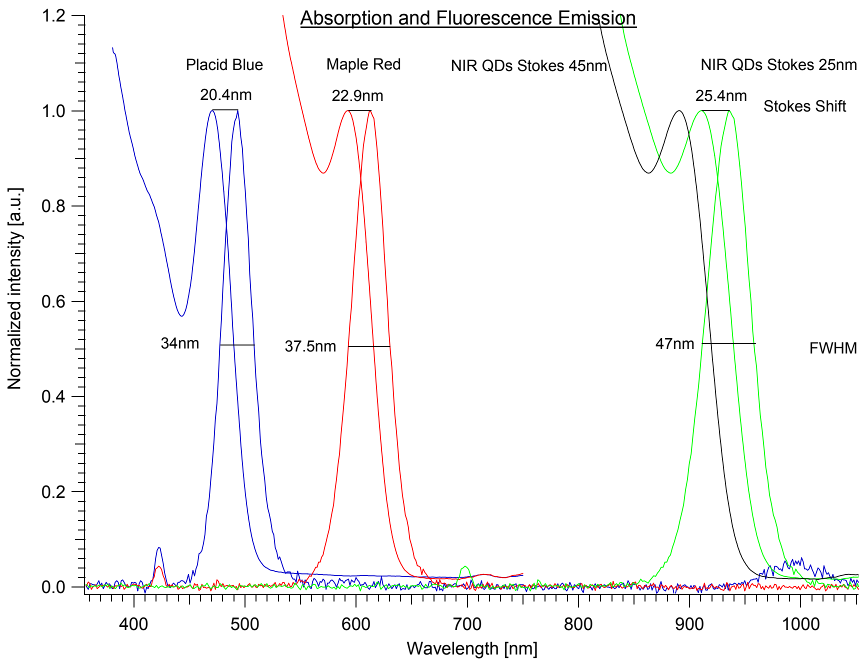


Fig.7: *Spectra of the absorption coefficient and the photoluminescent reemission as used in the simulations.*

Simulation of quantum dot solar concentrators

Because of the complexity of the problem we limited ourselves to devices consisting of a single concentrating pane (quantum dots contained in bulk or applied as coating) in combination with crystalline silicon PV cells. The obtained efficiencies do thus not yet represent an upper limit, higher efficiencies can be obtained for stacked devices (e.g. tandem or triple stacks) in combination with PV cells made of different semiconductors materials with matched band gaps.

In general, the performance of the devices is strongly dependent on the concentration of the quantum dots. The simulation is a powerful tool to optimize this important parameter.

The simulations were run with the following settings:

- Illumination with solar spectrum AM 1.5 Global
- Angular distribution of the incoming photons according to Moon and Spencer distribution
- One million incoming photons
- Optimized molar concentration
- Internal Quantum Yield of 85%

Important output parameters are

- The photovoltaic concentration, indicating the ratio of the electrical power produced by the cell when being illuminated with the concentrated radiation and the electrical power produced by the cell when being illuminated with the AM1.5 global spectrum. Data on the Quantum Efficiency of the photovoltaic cell were provided by the group of Prof. C. Baillif.
- The “maximum photovoltaic concentration”, that is the same ratio although the Quantum Efficiency is replaced by a step function adapted to the emission spectrum.
- The electrical power produced by the concentrator in the situation where a crystalline silicon solar cell produces $200W/m^2$ (1000W of solar radiation converted with an efficiency of 20%) .

An overview of significant results is given in Table 1. A surface of $1m^2$ is considered, with 1000W of incident solar radiation. The optical density of the photoluminescent material was optimized for each type of material. For commercial CdSe/ZnS core shell quantum dots, the simulation yields only an efficiency of 0.8%. For fluorescent dye colored PMMA, an efficiency of 1.5% is obtained. Higher efficiency values can be obtained for NIR-emitting quantum dots. For a Stokes shift of e.g. 65 nm, an efficiency of 5.3% is achieved, yielding under the given conditions an electricity production of 53W. This can be easily explained by the fact that the emission by the infrared emitting QDs is spectrally much better matched to the to the band gap of the crystalline silicon PV cell. In practice, the assumed Stokes shift of 65nm is not out of reach: CdS nanocrystal containg SiO_2 coatings produced by our laboratory exhibit a Stokes shift in the order of 60nm.

If the optical density of the material is reduced, the devices can even be made to be partially transparent. According to our simulations, a photovoltaic window containing one concentrating pane can produce above $26W/m^2$, while exhibiting a visible transmittance above 40%.

One important question is whether more or less advantageous to apply the quantum dots embedded in a coating on a transparent substrate, or if the quantum dots are dispersed in the entire volume of the pane. In corresponding simulations we compared QDs contained in a 0.1 mm thick coating on one or two sides of the substrate to QDs immersed in the bulk material. Basically the same results are obtained: **No losses** are implied when the quantum dots are contained in a coating and not in the bulk material.

More simulation results related to the optimization such devices are given in the laboratory report of Benjamin Huriet.

	VIS QDs CdSe/ZnS, Maple Red	fluor. dye col. PMMA, Red	NIR QDs (Stokes 25 nm)	NIR QDs (Stokes 45nm)
Dimensions [cm]	0.5*100*100	0.5*100*100	0.5*100*100	0.5*100*100
Geometrical Ratio	50	50	50	50
Quantum Yield ext.	18.9	28.8	18.0	32.7
CPDN	9.5	14.4	9.0	16.3
Photon concentration	2.5	4.5	7.3	12.9
CPDB	1.3	2.3	3.7	6.5
Energetic Concentration	1.6	2.9	3.1	5.6
Transmission at 550nm	43.2		4.6	5.7
Visible Transmission	51.1	51.3	5.0	5.0
Photovoltaic Concentration	2.0	3.7	5.1	9.4
PV Concentration Max	3.7	5.5	5.9	10.4
Efficiency (without trans)	0.8%	1.5%	2.1%	3.8%
Electrical Power prod.	8W	15W	**21W**	**38W**

	NIR QDs (Stokes 65nm)	NIR QDs (Stokes 85nm)
Dimensions [cm]	0.5*100*100	0.5*100*100
Geometrical Ratio	50	50
Quantum Yield ext.	46.7	54.0
CPDN	23.4	27.0
Photon concentration	17.8	19.7
CPDB	8.9	9.9
Energetic Concentration	7.8	8.7
Transmission at 550nm	4.2	4.9
Visible Transmission	4.8	4.6
Photovoltaic Concentration	13.3	15.0
PV Concentration Max	15.1	16.8
Efficiency (without trans)	5.3%	6.0%
Electrical Power produced	**53W**	**60W**

Table 1: Overview on parameters used in a series of Monte-Carlo simulations of quantum dot solar concentrators and obtained results, the latter including the predicted system efficiency and the electrical power produced.

5. Discussion

For single pane devices based on NIR emitting QDs in combination with crystalline silicon PV cells, system efficiencies up to 5% - 6% are expected. This is approximately in the same order of the efficiencies of amorphous silicon PV cells, but the sol-gel coatings could be produced at very low cost on the large scale, without the need for expensive vacuum eqiupment. System efficiencies will be higher when tandem or triple stack devices are built, in combination with high efficiency cells of different semiconductor materials with suitable energy gaps.

The predicted efficiency values given above might be to pessimistic, in reality even higher efficiencies might be achieved: For VIS emitting CdSe/ZnS quantum dots (EVIDENT Technologies, “Maple Red”), in combination with crystalline silicon PV cells, we obtained 0.8% maximum efficiency. Researchers from the European Project “FULLSPECTRUM” claim 1.8% efficiency for their device (as pointed out by S. Nowak, *OFEN, Programme Photovoltaïque, Rapport de synthèse du programme de recherche 2006*, p.7). It would be interesting to compare quantum dot and cell types of the simulated/measured devices, or to simulated their device using our software.

By our simulations, the importance of two main factors is revealed, an emission spectrum matched to the spectral efficiency curve of the photovoltaic cell, and a large Stokes shift, which is advantageous for the lateral energy transport. CdS nanocrystal containg SiO_2 coatings produced by our laboratory exhibit a Stokes shift in the order of 60nm. It should be feasible to replace the CdS in our coatings by another semiconductor such as e.g. PbS, thus aiming at a combination of the two beneficial factors.

Nanocomposite materials can be very durable. In selective solar absorber coatings, metal nanocrystal containing films have proven excellent stability in accelerated aging tests designed for a service lifetime over 25 years in harsh conditions (elevated temperatures and humidity). Silicon dioxide is an effective oxidation barrier: In food packaging, already a 2nm thin SiO_2 layer is sufficient to create an oxygen-tight protective layer. Therefore we believe that nanocomposite coatings consisting of inorganic semiconductor nanocrystals embedded in a silicon dioxide host matrix will show superior aging stability.

By sol-gel processing, large surfaces can be coated at low price. As an example, the German CENTROSOLARGLAS company can be mentioned: for sol-gel anti-reflection coatings on solar thermal collector glazing, the market prize amounts to only 8 EUR/m^2. Here lies one of the strengths of the concept: large surfaces could be coated in a low-cost process, resulting finally in low cost per kWh electricity.

6. Conclusions

- A large Stokes shift is advantageous in order to avoid energy losses during the lateral energy transfer. Our CdS nanocrystal containing coatings exhibit such a large Stojes shift.
- The photoluminescent emission of the quantum dots should spectrally match the used PV cells: e.g. for crystalline silicon PV cells, near infrared emitting QDs should be used (e.g. PbS nanocrystals).
- Quantum dots can be contained in a coating instead of being dispersed in the entire volume of the pane. No losses are implied due to the fact that the quantum dots are applied as a (nanocomposite) coating.
- Quantum dot containg sol-gel coatings can be applied at low price, quantum dots do not need to be purchased, crystals can be grown by self-organization during the thermal annealing step.
- Nanocomposite coatings consisting of inorganic semiconductor nanocrystals embedded in a silicon dioxide host matrix will be very durable.
- For single pane devices based on NIR emitting QDs in combination with crystalline silicon PV cells, system efficiencies above 5% - 6% are expected. For stacked devices, system efficiencies can be above 6%.
- combining cost-effective sol-gel deposition, high durability and system efficiencies > 6%, **the novel concept has a high potential and definitely merits future development.**
- The **next step** should be the development of coatings containing **NIR-emitting quantum dots** made of a semiconductor material with suitable band gap (e.g. PbS). Replacing the VIS-emitting CdS QDs in our coatings by NIR-emitting PbS QDs should be possible without any difficulties.

Symbols and Abbreviations

AM 1.5 Global	spectrum of global (direct and diffuse) solar radiationat air mass 1.5
CPC	Compound Parabolic Concentrator
CPDN	photonic concentration density net, the concentrated photon density over the absorbed photon density
CPDB	photonic concentration density brut, the concentrated photon density over the incident photon density
FWHM	Full width at half maximum
n_1, n_2	refractive indices of media 1 and 2
QD	quantum dot, semiconductor nanocrystal
ψ, α	angles used for the description of the state of light polarization

References

[1] Schüler A., Python M., Valle del Olmo M., de Chambrier E., ***Quantum dot containing nanocomposite thin films for photoluminescent solar concentrators,*** Solar Energy 81, 1159 (2007)

[2] Schüler A., Kostro A., Galande C. , Valle del Olmo M., de Chambrier E., Huriet B., ***Principles of Monte-Carlo ray-tracing simulations of quantum dot solar concentrators***, Proceedings of the ISES solar world congress 2007, Beijing, China 18th - 21st September 2007

[3] Kostro A., Huriet B., Schüler A., ***PhotonSim: developing and testing a Monte-Carlo ray-tracing software for the simulation of planar luminescent solar concentrators***, Proceedings of the CISBAT 2007 International Conference, Lausanne 4th - 5th September 2007

[4] Barnham J., Marques J.L., Hassard J., O'Brien P., 2000. ***Quantum-dot concentrator and thermodynamic model for the global redshift***, Appl. Phys. Lett. 76, 1197-1199.

[5] Batchelder J.S., Zewail A.H., Cole T., 1981. ***Luminescent solar concentrators. II. Experimental and theoretical analysis of their possible efficiencies,*** Applied Optics 20, 3733-3754

[6] De Mello Donegá C., Hickey S.G., Wuister S.F., Vanmaeckelbergh D., Meijerink A., 2003. ***Single-step synthesis to control the photoluminescence quantum yield and size dispersion of CdSe nanocrystals***, J. Phys. Chem. 107, 489-496.

[7] Gallagher S.J., Eames P.C., Norton B., 2004. ***Quantum dot solar concentrator, predicted using a ray trace approach***, Intern. Journal of Appl. Energy 25, 47-56.

[8] Goetzberger A., Greubel W., 1977. ***Solar energy conversion with fluorescent collectors***, Appl. Phys. 14, 123-139.

[9] Hines M.A., Guyot-Sionnest P., 1996. ***Synthesis and characterization of strongly luminescing ZnS-capped CdSe nanocrystals***, J. Phys. Chem. 100, 468-471.

[10] Nozik, A.J., 2002. ***Quantum dot solar cells***, Physica E 14, 115-120.

[11] Oelhafen P., Schüler A., ***Nanostructured materials for solar energy conversion***, Solar Energy *79*, 110 (2005)

[12] Winston R., 1974. ***Solar concentrators of a novel design***, Solar Energy 16, 89

Oral presentations

A. Schüler, ***Nanostructured materials in solar energy conversion***, ***invited talk***, Seminar of Condensed Matter Physics, Institute of Physics, University of Basel

A. Schüler, ***Principles of Monte-Carlo ray-tracing simulations of quantum dot solar concentrators***, ISES solar world congress 2007, Beijing, China 18th-21st September 2007

A. Kostro, ***PhotonSim: developing and testing a Monte-Carlo ray-tracing software for the simulation of planar luminescent solar concentrators***, CISBAT 2007 International Conference, Lausanne 4th - 5th September 2007

Dissemination

Documentary ***NZZ Format: Sonne - Zukunftsenergie und Wirtschaftsmotor***, on Swiss German television channel **SF2**, 09/09/2007, 21.30h.

A considerable part of the movie was shot in our laboratory, concerning the topics of novel colored glazing for solar thermal facade collectors, and on quantum dot solar concentrators.
The movie is available on DVD from SF2.

Awards

ABB Innovation Award 2007

André Kostro, ***Photonsim: development of a Monte Carlo ray tracing software for the simulation of photoluminescent solar concentrators***

Solar Energy Journal Best Paper Award 2005 - 2007
ISES world congress 2007, Beijing, China

Best Full Length Paper in Energy Conversion:

Nanostructured materials for solar energy conversion

Peter Oelhafen and Andreas Schüler

Solar Energy Vol. 79, No.2, pp.110-121