Proof of Down-Conversion by CdSe/ZnS Quantum Dots in Silicon Solar Cells

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I. INTRODUCTION

Luminescence down-conversion (LDC) is one of the spectral engineering approaches [1-4] that can improve solar cell performance by means of absorption and emission in luminescence centers such as rare-earth ions [5], dyes [6] and quantum dots (QDs) [1, 7, 8]. The wavelength of the incident photons can be down-converted, from the wavelengths where the spectral response of the solar cell is low, to the wavelengths where the spectral response of the cell is high.
High brightness, stability and broad absorption band are the advantages of QDs with respect to other luminescent materials, which makes them potential candidates for use in down-conversion layers [7, 8].

Since LDC is a passive approach, it eliminates any interference with the active material of a photovoltaic (PV) device which is technically favorable. Hence, the method does not add any complication to the production of the existing device. One [illegible] a reference cell. The improved performance of cells with LDC layers proved the QD down-conversion effect.

II. METHODOLOGIES FOR LDC LAYER FORMATION

A. *Structural Characteristics of CdSe/ZnS in Liquid Form*

Core/shell CdSe/ZnS QDs dispersed in toluene and stabilized in octadecyl amine (ODA) were purchased from a commercial supplier. Fig. 1 exhibits the Transmission Electron Microscope (TEM) image of the QDs prepared by drop-casting a diluted solution onto a carbon coated copper grid. The QDs average particle size is 6nm and they are well separated from one another with no agglomeration. The lattice structure of the QDs in the zone axis is clear in the high resolution (HR)-TEM image, indicating their Wurtzite crystalline structures (see inset in Fig. 1). The thickness of the shells is about 6nm and the unclear interface between the CdSe core and ZnS shell is due to the epitaxial growth of the shell and small lattice mismatch between the core and the shell.

Fig. 1. TEM micrograph of core/shell CdSe/ZnS QDs, inset the

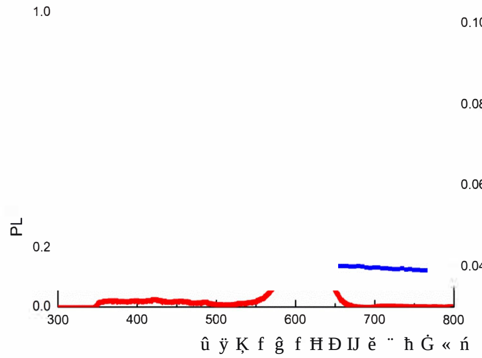

Fig. 2. Absorption/emission spectra of 6nm core/shell CdSe/ZnS QD layer

Introducing the 6nm QDs in the LDC layer results in absorption of photons with wavelengths smaller than 620nm, where the response of the cell is low; and down-converting them to the longer wavelength (620nm), where the response of the cell is high. Hence the strongest LDC effects were expected to be seen.

For layer formation, CdSe/ZnS QDs from the colloidal solution were spin cast on the substrate in a glovebox under controlled ambient. Spin coating conditions were controlled for the concentrated and diluted ensemble of CdSe/ZnS quantum dots to obtain thin films containing CdSe/ZnS with a specific thickness, QD concentration and uniformity for achieving the highest gain from the LDC layer. Fig. 3 demonstrates the TEM image of a QD layer formed by spin casting from a 5mg/mL colloidal solution onto a silicon substrate at 1000 rpm for 30s. The substrate is isolated from the QDs with a thin silicon nitride film. The layer was then capped with a spin on glass (SOG) film.

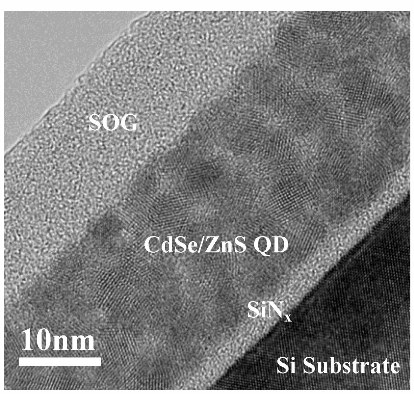

Fig. 3. HRTEM image of a crystal structure of the QDs which uniformly deposited on a thin transparent silicon nitride film and capped with SOG

The excitation and emission scans were performed on the QD solution in an integrating sphere. The absolute value of 85% for the quantum efficiency was determined.

Fig. 4 demonstrates the emission map of the LDC layer at different excitation wavelengths ranging from 300-600nm.

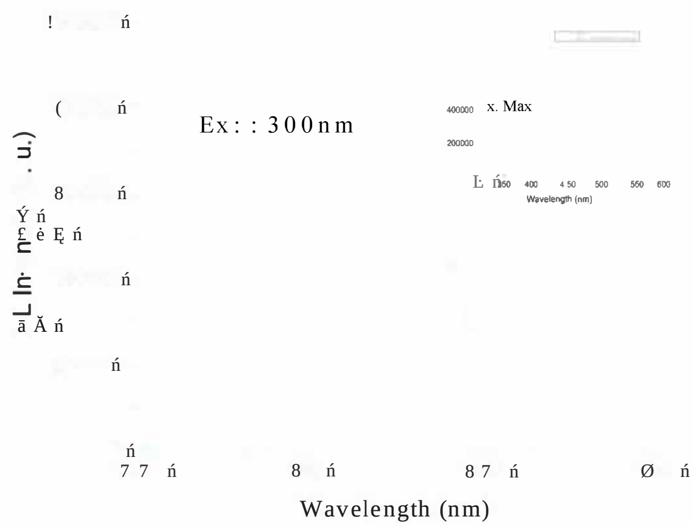

Fig. 4. CdSe/ZnS QDs emission map at excitation wavelengths in the 300-600nm range. Inset is the QD excitation spectrum at emission maximum.

The spectrum depicts that the emission intensity is about two-fold higher at the excitation wavelengths, in the range of 300-380nm, which is about two times the bandgap of crystalline silicon. The inset shows the QD excitation spectrum at QD emission maximum which also shows that the QDs have the highest efficiency at 300-400nm with the excitation peak intensity at 320nm. Therefore the DC effect should be more pronounced in this range.

III. DEVICE CONFIGURATION w PERFORMANCE

x s *Device Configurations with LDC Layers*

The device configurations that were studied are depicted in Fig. 5. In the first architecture, QDs were spin-cast on top of the c-Si solar cell with an 80nm silicon nitride layer used as anti-reflection coating (ARC) and for isolation of the QDs from the cell. In the second architecture, the QDs were fully buried in an SOG transparent layer. The thickness and transparency of the SOG layer needs also to be optimized for effective LDC performance.

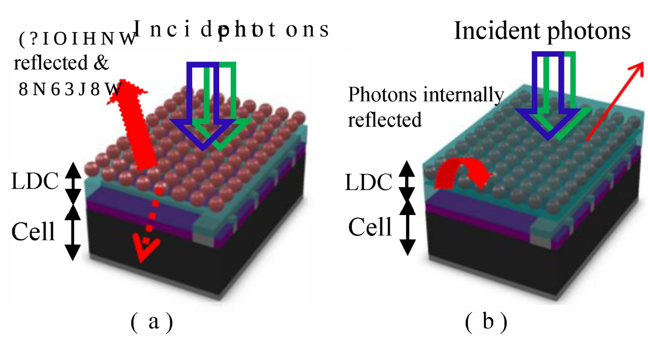

Fig. 5. Schematic diagram of cells with a) QD layer and b) QD layer capped with SOG used as LDC layers

benefits from some down-converted photons. Also, the reflectance and absorption is less for the LDC layer with lower QD concentration.

The illuminated current-voltage (IV) characteristic of the cells with and without the LDC layer is also compared in Fig. 11. From the IV result, it is apparent that the current density and the overall cell efficiency are improved for the cell with the LDC layer containing a lower QD concentration.

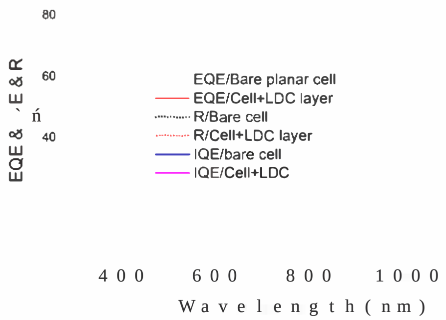

Fig. 10. EQE, IQE and reflectance characteristics of 2×2 cm^2 planar cell with an LDC layer containing low QD concentration

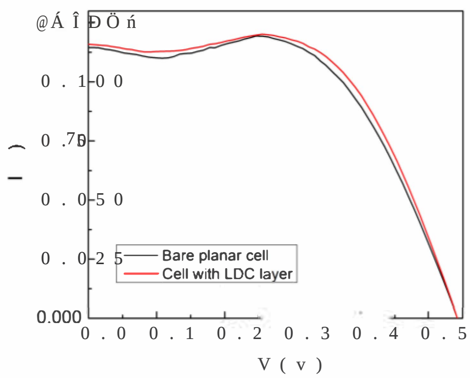

Fig. 11. IV characteristics of 2×2 cm^2 planar cell with an LDC layer containing low QD concentration

In order to determine the effect of the cell size on the LDC, the QD layer was deployed on the 1×1 cm^2 cell. Figures 12 and 13 show improvements in the quantum efficiency and illuminated IV characteristics of the cell with an LDC layer, respectively. The results shown in Fig. 12 also exhibit that the absorption and reflectance of the LDC layer were better controlled in the smaller cells.

Table 1 demonstrates the illuminated IV characteristics of the planar cells with small and big dimensions and high and low QD concentrations. 2 ïń and 0.31% improvement in current density and cell efficiency were obtained respectively for the cells with LDC layer containing a lower concentration of QDs.

An LDC layer containing low QD concentration was also deployed on 1×1 cm^2 textured cells (see Fig. 14). The results show lower reflectance in the cell with LDC as compared to reflectance previously obtained for the LDC containing highly concentrated QDs. However, no improvement was observed in the overall efficiency of the device.

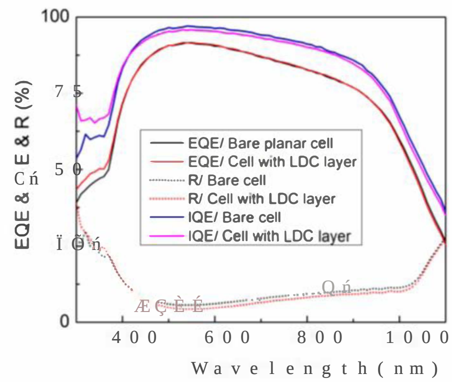

Fig. 12. EQE, IQE and reflectance characteristics of 1×1 cm^2 planar cell with an LDC layer containing low QD concentration

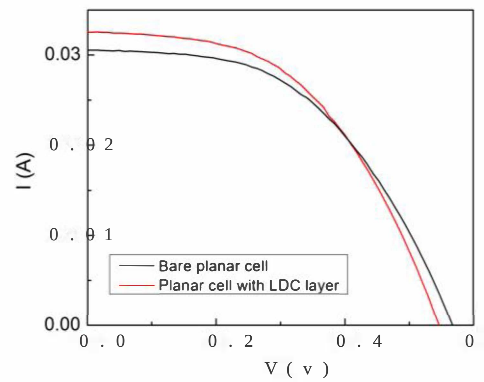

Fig. 13. IV characteristics of 1×1 cm^2 planar cell with an LDC layer containing low QD concentration

TABLE I
ILLUMINATED IV CHARACTERISTICS OF LABORATORY SCALE PLANAR SOLAR CELLS WITH AND WITHOUT LDC LAYER

	ô :ĐĢĐ loñĩ :ĐĄ ñ: : o ń	Voc (V)	Jsc (rA)	Z Z ń (%)	¤ ń (%)	Area (cm^2)
1	3L8W6EBNWG3NE@W8 W ?@>)?W6IH68HOL3O@IHW	W	W	W	W	1
/	8EE # NG3NE@W8 W ?@>)?W6IH68HOL3O@IHW	W	W	W	W	1
3	3L8W6EBW5N@WV8 W ?@>)?W6IH68HOL3O@IHW	W	W	W	W	W
Ô ń	8EE # W5@N@WV8 W ?@>)?W6IH68HOL3O@IHW	W	W	W	W	W
5	3L8W6EBNWG3NE@W8 W #ISW W6IH68HOL3O@IHW	W	W	W	W	1
/	8EE # NG3NE@W8 W #ISW W6IH68HOL3O@IHW	W	W	W	W	1
	3L8W6EBW5N@WV8 W #ISW W6IH68HOL3O@IHW	W	W	W	W	W
U ń	8EE # W5@N@WV8 W #ISW W6IH68HOL3O@IHW	W	W	W	W	W