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Purcell effect and luminescent downshifting in silicon nanocrystals coated back-contact solar cells



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ABSTRACT

Silicon nanocrystals show a significant shift between the strong absorption in the blue–ultraviolet region and their characteristic red–near-infrared emission as well as space separated-quantum cutting when short wavelength photons are absorbed. These two effects can be used to increase the efficiency of crystalline silicon solar cells. We fabricated high quality interdigitated back-contact crystalline silicon solar cells in an industrial pilot line and coated them with optimized silicon nanocrystals layers in a cost effective way. Here we demonstrate an increase of 0.8% of the power conversion efficiency of the interdigitated back-contact cell by the silicon nanocrystals layer. In addition, we prove that this increase is due to a combination of a better surface passivation, a better optical coating, and of the luminescent downshifting effect. Moreover we demonstrated that the engineering of the local density of photon states, thanks to the Purcell effect, is instrumental in order to exploit this effect.

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1. Introduction

Production of photovoltaic cells is dominated by single junction devices based on crystalline silicon [1], which account for about 90% of the world total photovoltaic cell production. Considerable progresses in increasing the efficiency of crystalline silicon solar cells have been made by minimizing photon, carrier and electrical losses through new cell structures and processes, such as interdigitated back-contact cells (IBC) or heterojunction cells with intrinsic thin layer [2]. At the same time, enormous interest raised in novel approaches-third generation photovoltaic-aimed at increasing the efficiency with new concepts [3]: improved light harvesting [4–7], minimization of hot carrier losses by promoting fast and non-dissipative recombination mechanisms [8–12], and modification of the solar spectrum through photon conversion [13,14]. In this context the exploitation of luminescent downshifting effect (LDS) and space separated-quantum cutting (SSQC)

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http://dx.doi.org/10.1016/j.solmat.2014.09.007 0927-0248/© 2014 Elsevier B.V. All rights reserved. [12] is of special interest, allowing the combination of different concepts to improve the cell efficiency with practical production technologies.

The basic idea of LDS is to move short-wavelength photons to long wavelength photons [13]: a range where silicon solar cell has almost 100% internal quantum efficiency (IQE). In this way, the short circuit current density (I_{sc}) is increased while the open circuit voltage (V_{oc}) is barely affected [13]. Up to now, LDS has not been engineered in an effective way. A few successful reports demonstrated industrialization of LDS by using phosphor doped ethylene vinyl acetate with an increase of 0.3% in module efficiency [15] or by using inkjet printing with a relative increase in the cell efficiency of 2% [16]. Interestingly, many reports address the use of silicon nanocrystals (Si-NCs) as suitable candidates for LDS [16–19]: these nanoparticles are stable, bright, show a significant red-shift between emission and absorption [20], and can be manufactured by using standard deposition techniques. In addition, SSQC in Si-NCs has also been reported [8-12]. This process involves the transformation of a high-energy photon into two or more photons of lower energy, hence "cutting" the energy quantum [12]. Ideally, the down-converted photons are in a suitable range of the spectrum and can be further used without loss of energy. A similar idea involves the generation of multiple electron-hole pairs by a single high-energy photon absorbed in a nanocrystal. This process, called multiple exciton generation, can be used as an internal gain process in the solar cell. Indeed, a peak external quantum efficiency exceeding 100% has been reported for PbSe quantum dot solar cells exploiting multiple exciton generation [21].

In this paper, an innovative method is presented to fabricate interdigitated back contact silicon crystalline solar cells in an industrial pilot line [22] coated by an optimized Si-NCs layer in a cost effective way [23]. An improvement in the power energy conversion efficiency of 0.8% was measured. We prove that this increase is due to a combination of different effects: a better surface passivation, a better optical coating, LDS effect, and that the engineering of the local density of photon states is instrumental in order to exploit this effect.

2. Materials and methods

To exploit LDS stemming from Si-NCs implemented directly on solar cells, we fabricated interdigitated back contact solar cells on $25 \,\Omega \cdot \text{cm}$ n-type doped float-zone silicon wafers with bulk minority carrier lifetime higher than 5 ms coated with Si-NCs in an industrial process [22]. The wafer thickness (160 μ m) guarantees a high collection efficiency of the minority carriers. All wafers were saw-damage etched in a 22% NaOH solution, resulting in chemically polished surfaces. Prior to the diffusion processes, the wafers were cleaned in a 5% HCl, 2% HF and a piranha solution (i.e., 6:1 mixture of concentrated H₂SO₄ and 30% H₂O₂), with DI water dips in between every step. The subsequent process involved the formation of the front surface field (FSF) and the back surface field (BSF) by phosphorus doping with oxychloride (POCl₃) as a diffusion source in an industrial-size guartz tube furnace, followed by a plasma enhanced chemical vapour deposition (PECVD) of a dielectric mask on the BSF side and etching of the phosphorus silicate glass. At this stage of the process the solar cells were coated, on the FSF side, with an optimized 55 nm-thick SiO₂ and 65 nm-thick silicon rich oxide (SRO) double-stack antireflection coating (ARC) to fabricate Si-nanostructured solar cells or by an optimized 75 nm-thick SiN_x and 5 nm-thick SiO₂ double ARC layer to develop industry-standard IBC solar cells. In the next process step, the interdigitated pattern on the backside was accomplished by laser ablation of the mask layer followed by a laser-damage etch and surface cleaning (as described before). A p⁺ emitter was then formed in the ablated areas by boron tribromide (BBr₃) tube diffusion. After borosilicate glass etching and another surface cleaning, the backside of the IBC cells was passivated by a 20 nm-thick thermal SiO_2 and about 60 nm-thick SiN_x doublelayer stack. The cell fabrication was then completed by metallization using standard screen-printing of an Ag paste (for BSF) and an Ag/Al paste (for emitter), with a subsequent contact-firing step. For more details on the used process flow, see the Supplementary information.

Si-NCs in a SiO₂ matrix were produced by thermally induced phase separation of the SRO layer. During the high temperatureannealing step (1100 °C for 1 h), Si-NCs nucleate within the SRO layer [24]. The main problem concerning the integration of this active element into the cell manufacturing process is the high temperature-annealing step necessary for the nanoparticles formation. This additional thermal treatment takes place at significantly higher temperature than the typical diffusion temperature used to form the emitter or the back/front surface field regions. As a consequence the whole IBC cell process will be affected, resulting in lower solar cell performances. In order to overcome this drawback, we integrated the annealing within the IBC cell process steps. Particular care was taken in order to depart as little as possible from the standard industrial process used to produce the IBC cells [22]. For that matter the SiO₂/SRO double-stack layer was deposited at the stage when in the standard process the passivation layer was deposited on the front side, while the annealing step used to drive in the dopants was adapted to be also used to induce the Si-NCs in the SRO. In more detail, by carefully adapting the temperature profile during initial POCl₃ diffusion, we successfully incorporated the annealing of Si-NCs in-situ during the subsequent BBr₃ diffusion, thus further reducing the number of process steps and fabrication cost of the solar cells. The entire IBC cell process presented here uses only fabrication techniques readily available in most pilot production lines, making such an approach relevant for commercialization. Reference industrystandard solar cells (named REF in the following) were also fabricated with the same batch processing. In this case, an optimized 75 nm-thick SiN_x and 5 nm-thick SiO₂ double stack ARC layer was used on the front side, as described above. This layer was made via PECVD deposition. For more details on the thickness optimization, see the Results and discussion section. In addition it should be mentioned that these cells are fabricated on flat surface (not textured), resulting in a lower photocurrent generation. It was not possible to fabricate Si-nanostructured IBC textured solar cells due to technical issues in processing textured surfaces together with the nanoparticles formation.

The total reflectance spectra of the Si-nanostructured and reference IBC solar cells were measured with a Perkin-Elmer Lambda 950 spectrometer using an integrated sphere to 150 mm. The measured total reflectance *R* was converted to the total absorption (1-R) and used to extract the internal quantum efficiency from the external quantum efficiency measurement. In order to study the optical properties of the different double stack ARC layers, we used a variable angle spectroscopy ellipsometer (VASE) to measure the refractive index and their thicknesses. The ellipsometric spectra were measured from 0.28 to 1.2 µm at different angles and the dielectric function, and then the refractive indices were obtained by a standard least square regression analysis. The Si-NCs photoluminescence spectra were obtained by using the 355 nm line of a Nd:YVO₄ laser to excite the samples at normal incidence.

To isolate the LDS effect from the other contributions to the short circuit current increase, we used two different approaches. In the first approach we have deposited, via PECVD, an optimized 130 nm of SRO layer on 500 μ m thick amorphous quartz substrate. In the second method a colloidal suspension of Si-NCs in glycerol, obtained from sonification of porous silicon as described in [25], was used. In this study the J_{sc} measurements were performed using an ABET sun 2000 solar simulator class AAB and a Keithley source-meter series 2612 A. A Peltier element coupled with a Pt100 was used to control the temperature of the cell (23 ± 1 °C) during the experiments.

3. Results and discussion

Optimization of the layer thicknesses with respect to low reflectance, high absorbance and maximum emission is needed to maximize the solar cell performances [18]. Using the model presented in [18], we have optimized a SiO₂/SRO double layer stack on top of a silicon substrate in order to yield maximum short circuit current density. To perform this optimization, we used the measured internal quantum efficiency of the IBC cell. Further, we used the measured refractive index of an annealed SRO layer (Fig. 2d). The refractive indices of the other materials were taken from the database of the thin film modelling software Scout[®] [26]. Fig. 1 shows the results of these calculations for both the REF and



Fig. 1. Thickness optimization simulations. (a) 3D plot of the simulated J_{sc} in mA/cm² as a function of the SiN_x and SiO₂ thicknesses. (b) Contour plot of the optimal zone. The marker refers to the thickness combination that maximizes J_{sc} and that was used to fabricate the reference cells. (c) 3D plot of the simulated J_{sc} in mA/cm² as a function of the SiO₂ and annealed SRO thickness. (d) Contour plot of the optimal zone. The marker identifies the best thickness combination which was used to fabricate the Si-NCs cells.

Si-NCs IBC cells. 3D plots display the variation of J_{sc} as a function of the optimization parameters. Interference effects, which depend on both the refractive index and thickness of each layer, account for the oscillatory behaviour of the current. Therefore, the peaks in Fig. 1a and c correspond to the thickness combinations that maximize the integrated transmittance, i.e. the fraction of the transmitted light into the silicon substrate. For these values, the integrated surface reflectance is minimized due to the destructive interferences. For the REF cell, J_{sc} is maximized by 75 nm thick SiN_x and 5 nm thick SiO₂ (Fig. 2b) while, in the case of Si-nanostructured IBC device, the maximum value of the short circuit current density is obtained for a double layer stack of 55 nm of SiO₂ and 65 nm of SRO, as shown in Fig. 1d.

Fig. 2a shows the performances of IBC solar cells with (Si-NCs cells) and without (REF cells) silicon nanoparticles. The average J_{sc} is 2.5% higher while the average $V_{\rm oc}$ is less than 0.2% higher for the Si-NCs cells with respect to the REF cells. The average solar cell efficiencies are 16.9% and 16.7% with and without Si-NCs respectively, while the fill factor (FF) does not show any significant statistical variation. These results are based on multiple measurements performed on 26 nominally equal cells for each kind. Fig. 2b compares the IQE of Si-NCs and REF IBC cells. The Si-NCs cells show a larger IQE with a significant improvement in the ultraviolet region. Moreover, the IQE of the Si-nanostructured IBC cells is larger with respect to the REF also for longer wavelengths. This enhancement can arise from the improved anti-reflection. Indeed reflectivity measurements, shown in Fig. 2c, display a reduction of the optical losses by using the SiO₂/SRO double layer coating with respect to the SiN_x ARC layer. In more detail, the novel nanostructured coating decreases the reflectance in the wavelength range 0.29–0.48 and 0.71– 1.1 µm. The optical losses are reduced by ~12% at the maximum value of the reflectance (around 0.37 µm), as shown in the figure. The increased reflectance in the infrared region is produced by Fabry–Pérot interference due to the thick silicon substrate. The photoluminescence and the optical properties of the Si-NCs are shown in Fig. 2d. The expected 800 nm emission band and a rising extinction coefficient *k* at 400 nm are observed [19]. The refractive index dispersion of the Si-NCs film is also shown in the figure.

Fig. 3 shows the *J*–*V* curve of our best Si-NCs IBC device. This nanostructured solar cell has V_{oc} =652 mV, J_{sc} =38.1 mA/cm², and a fill factor (FF)=76% with 18.8% efficiency under AM1.5G illumination. For qualitative comparison, Fig. 3 also presents the *J*–*V* curve of our best reference cell coated by industry-standard ARC (see the Materials and methods section). The inset summarizes the V_{oc} , J_{sc} , FF and efficiency values of the solar cells shown in the figure. The silicon nanostructured antireflection coating enhances the optical absorption and increases the short circuit current density by ~0.7 mA/cm² compared with our best reference solar cell, and leads to a relative 4.4% (0.8% absolute) increase in efficiency. Moreover, this nanostructured solar cell has the advantage of reducing the number of process steps and, hence, the fabrication cost (see Materials and methods).

In summary, we observed that the efficiency increase of the Si-NCs cells with respect to the reference cells is due to a combination of the LDS effect (improved IQE in the ultraviolet could be attributed to the Si-NCs absorption in this spectral range and re-emission in the red), and improved surface passivation (higher IQE on the whole recorded range), improved ARC



Fig. 2. Optical properties of the Si-NCs and comparison of the IBC performances with and without Si-NCs. (a) Averaged short circuit current density (J_{sc}), open circuit voltage (V_{oc}), efficiency, and fill factor (FF) of the reference (REF) and Si-nanostructured (Si-NCs) solar cells. Error bars represent the standard deviation of the mean evaluated on at least 26 cells for both type of cells. (b) Internal quantum efficiency (IQE) of Si-NCs (blue line) and REF (red line) IBC solar cells. (c) Reflectance measurements of REF (red line) and Si-NCs (blue line) IBC cells. (d) Measured real (n, blue line) and imaginary (k, red line) part of the Si-NCs refractive index. The green points represent the Si-NCs emission as measured on the Si-NCs IBC cell. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



Fig. 3. J-V curves and solar cell parameters: J-V curves of 18.8%-efficient Si-nanostructured IBC (blue line) and best reference solar cell (red line) coated by industry-standard SiNx layer under AM1.5G illumination. The inset summarizes the solar cell efficiency and the J-V parameters. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

performance (due to a better optical matching because of the tailoring of the double stack layer). Note that a reduction of the surface recombination velocity due to a better surface passivation should also result in a significant increase of $V_{\rm oc}$ which is not observed in Fig. 2a. Therefore, we deduce that LDS is the dominant effect. The integration of the Si-NCs during the cell fabrication

process contributes effectively in increasing the cell efficiency without a significant increase in the cell cost [23].

To isolate the LDS effect from the other contributions to the short circuit current density increase, we deposited optimized silicon rich oxide layer on a 500 µm thick amorphous guartz substrate which was then used to cover a back contact solar cell coated by an industry-standard textured coating (see Fig. 4). Therefore, there is an optical coupling between the Si-NCs layer and the cell but not a physical contact: the sun light arriving to the cell is modified by the Si-NCs thanks to the LDS effect while the surface passivation of the cell is not affected by the presence of the nanoparticles. We split into two independent steps the fabrication process: first the manufacturing of the cell and second the nanoparticles fabrication. Repeated measurements were then performed using the same cell with different covers: one with only quartz (labelled reference cover), one with as-deposited silicon rich oxide layer on guartz, i.e. without annealing and thus no nucleation of the Si-NCs (SRO NA cover), and one with Si-NCs coated guartz (i.e., annealed SRO). The last two configurations were used to compare a pure coating effect (SRO NA cover) with a situation where both better optical coating and LDS are expected (Si-NCs cover). To validate this statement we measured the real and the imaginary parts of the different covers, as shown in Fig. 4a. Annealing of the silicon rich oxide causes the formation of the Si-NCs with a little change in the real part of the refractive index: from n = 1.6 to 1.7 at the Si-NCs emission wavelength (800 nm). Note that no emission is observed in the SRO NA cover configuration, as shown in Fig. 4b. Moreover, this figure displays the broad photoluminescence emission band of the Si-NCs. From its spectral position, we can estimate a particle average size of 4–5 nm [27].



Fig. 4. LDS contribution in the J_{sc} enhancement. (a) Real (*n*) and imaginary (*k*) parts of the refractive indices of the Si-NCs cover (blue line) and silicon rich oxide not annealed (SRO NA) cover (red line) measured by using variable angle spectral ellipsometry (VASE). The marker identifies the real refractive index value at 800 nm, i.e. the Si-NCs peak emission. (b) Photoluminescence (PL) signal of coated quartz samples. As expected the SRO NA does not show any PL signal, confirming the absence of Si-NCs. (c) A textured IBC device is capped with different covers, as explained in the text. We used different media in the spacing layer between the covers and the IBC cell: air, glycerol, and a liquid with a refractive index almost matching the one of the Si-NCs (RIML). (d) J_{sc} enhancement measured in the different configurations. The hashed colored bars refer to simulation while the colored bars to measurements. Red refers to an empty (air) spacing layer, orange to glycerol filled spacing layer, and light blue to RIML in the spacing layer. For all the data reported in this figure, we repeated 15 times the measurements by using the same covers. The error bars are evaluated with the standard deviation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In order to study the influence of the dielectric environment on the emission, we considered three different situations by changing the medium between the cell and the covers (see Fig. 4c). We left the space empty (air configuration), and filled it with glycerol (glycerol configuration), or with a refractive index matching liquid (RIML configuration, n=1.74 at 800 nm [28]). Using an AM1.5G illumination source, enhancement in J_{sc} with respect to the reference quartz covered cell has been observed only when Si-NCs are formed and the RIML was used. In this case a (1.2 ± 0.2) % relative enhancement with respect to the reference was observed (see Fig. 4b). Further, we used a configuration where a luminescent colloidal Si-NCs suspension in glycerol [25] was used to fill the spacing layer between the cover quartz and the cell, as shown in Fig. 5. The refractive index of these colloids is compared to that of glycerol in Fig. 5a. The similarity between the two indicates a dilute concentration of nanoparticles in the colloid. This active material shows a broad luminescence band, which peaks at 630 nm, indicating an average Si-NCs size of 2-3 nm [27], as shown in Fig. 5b. These colloids are red emitting when blue illuminated (Fig. 5b inset). Note worthily, in this configuration, a (2.3 ± 0.2) % enhancement of J_{sc} was measured with respect to a configuration where the same cell and the same glycerol were used but no Si-NCs were in suspension (see Fig. 5d). For more details, see Supplementary information.

Since exactly the same IBC cell was used during all the experiments, the surface passivation was not changed, i.e. the optical and electrical characteristic of the cell stay the same and the only variations are due to the different covers and filling media used. To estimate the optical coating contribution to the J_{sc}

enhancement, we simulated the transmission through the coated quartz for the configurations for which we experimentally observed the enhancement. These simulations were performed with the thin film software Scout[®] and by using, as input, the measured refractive indices shown in Figs. 4a and 5a. No emission from the Si-NCs was included in these simulations. Fig. 6 shows that, independently of the used cover, the same photon flux reaches the silicon substrate, excluding the ultraviolet region where the Si-NCs absorb. Whereas, simulations in which the LDS effect is considered are consistent with the experimental observations (Figs. 4d and 5d, hatched bars). These simulations were obtained by using the method presented in [18] with a Si-NCs quantum yield (QY), i.e. fraction of the absorbed light emitted by Si-NCs, of 20% in Fig. 4d and 30% in Fig. 5d. These assumptions on the OY are consistent with the data presented in [29] for the Si-NCs embedded in a SiO₂ matrix and in [25] for the colloidal solution.

Let us now explain the reason why only in the RIML and colloidal Si-NCs configurations J_{sc} enhancement was observed. This is due to the Purcell effect [30]: the spatial radiative emission pattern modification due to the variation of the local photon mode density of states (LDOS) caused by a different dielectric environment. Fig. 7 shows this effect considering the simple case of a single vertical dipole placed at the interface between two media of different refractive index. As the refractive indices of the bottom medium is increased, more emission is driven into it [31,32]. More precisely, we simulated the Si-NCs layer as an ensemble of random oscillating electric dipoles with different emission frequencies (see Supplementary information for more details). A total of 100



Fig. 5. LDS contribution in the J_{sc} enhancement. (a) Real refractive indices (*n*) of the Si-NCs in colloidal suspension in glycerol (blue) and of glycerol (red) measured by VASE. The marker identifies the real refractive index value at 630 nm, i.e., the colloidal Si-NCs peak emission. Imaginary refractive index (*k*) measurements were difficult due to the low concentration of the suspended Si-NCs and the high transparency of glycerol. (b) PL spectra of two Si-NCs colloidal suspensions used. The inset shows optical images of the colloids under UV illumination. (c) Scheme of the configuration where colloidal Si-NCs are used as an active liquid in the quartz-cover/IBC cell. (d) J_{SC} enhancement. The inset shows the visible emission of the active liquid under an UV lamp illumination when it is encapsulated in the quartz-cover/IBC cell. For all the data reported in this figure, we repeated 15 times the measurements by using the same cover. The error bars are evaluated with the standard deviation of the mean in the repeated measurements. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



Fig. 6. ARC contributions in the J_{sc} enhancement. (a) Simulated transmission into the silicon substrate produced by the Si-NCs (blue), SRO NA (green), and quartz covers (red) in the RIML configuration. The oscillations are related to Fabry–Pérot interferences caused by the quartz (500 µm) and the spacing layer ($\approx 200 \mu$ m) thickness. (b) Simulated transmission into the silicon substrate for glycerol (red) or colloidal Si-NCs (blue) in the cover-glass/IBC spacing layer. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

oscillating electric dipoles randomly distributed, with random phases as a function of the time, and with different emission frequencies were used. In this way, the ensemble of electric dipoles generates incoherent emission. They were further placed in a three stacks system with proper refractive indices to model the various configurations. Then, we computed the fraction of the emitted optical power propagating into the different layers. These simulations were performed with the finite-elementdomain method. The mesh resolution was set to have a high resolution around the sources and around the detectors placed in the far field. Scattering boundary conditions were assumed in all calculations to circumvent reflection effects of the emitted light



Fig. 7. Radiation pattern of a dipole in different environments: the emitter is placed at the centre of the simulation plane (electrical dipole is oriented along the vertical direction) while the refractive index material of the lower half-plane (n_{bottom}) is gradually changed. (a) Free space. (b) n_{bottom} =1.5. (c) n_{bottom} =2.5. (d) n_{bottom} =3. The emission pattern becomes highly directive as n_{bottom} increases: the critical angle θ_C decreases.

Table 1

Simulation of the spatial distribution of the Si-NCs emission due to different cell structures.

	Silicon		Colloidal Si-NCs		Air		Glycerol		RIML	
	n	%	n	%	n	%	n	%	n	%
Quartz Active layer Substrate	1.4 1.8 3.7	$\begin{array}{c} 38.8 \pm 0.5 \\ 1.2 \pm 0.1 \\ 60 \pm 0.5 \end{array}$	1.4 1.44 3.88	$\begin{array}{c} 38.7 \pm 0.5 \\ 2.5 \pm 0.2 \\ 58.8 \pm 1 \end{array}$	1.4 1.7 1	$\begin{array}{c} 60.7 \pm 2.5 \\ 0.5 \pm 0.1 \\ 38.8 \pm 2.6 \end{array}$	1.4 1.7 1.43	$\begin{array}{c} 48.4 \pm 0.2 \\ 0.8 \pm 0.1 \\ 50.8 \pm 0.1 \end{array}$	1.4 1.7 1.75	$\begin{array}{c} 40.5 \pm 2.2 \\ 0.5 \pm 0.04 \\ 59 \pm 2.2 \end{array}$

with the edges of the simulation plane. The results are summarized in Table 1. The different columns are labelled according to the different cell structures: silicon refers to the Si-NCs IBC cell; colloidal Si-NCs refers to the cell where a Si-NCs colloid is placed between the silicon cell and the cover glass; the last three columns refer to cells where a Si-NCs coated quartz is used to cap the silicon cell and different media are placed in between: air, glycerol and a RIML liquid. Emission power distribution is computed by considering a multi-layer system where the Si-NCs are placed in the active one. Only the layers embedding the active one are here reported in the various rows (Supplementary gives the specific structure). The first row refers to a SiO₂ layer (for the Si-NCs IBC cell) or to a quartz layer (all the others). The second row gives the results for the active layer, which is modelled by randomly distributing the Si-NCs in it. The last row is the substrate on top of which the active layer is placed. In the first two configurations, the substrate is the silicon cell. In the last three configurations the substrate is the medium, which fills the space between the quartz cap and the silicon cell. The composition of the substrate in these last configurations is reported in the column heading. Then, by integration of the emitted power in the respective layer the normalized power distribution, reported in the columns labelled by %, is computed. Many simulations (at least 6) were performed with the same configuration to take into account the effect of the random parameters on the radiated power. The errors are the standard deviations. At the end *n* indicates the values of the refractive index of the specific layer at 800 nm, i.e. at the peak wavelength of the Si-NCs embedded in a SiO₂ matrix for all the configurations (see Figs. 2d and 4b) except the colloidal Si-NCs scheme where the emission is peaked at 630 nm (see Fig. 5b) and, therefore, n is specified at this wavelength.

When air is used to fill the spacing layer between the cover quartz and the IBC cell, most of the emission is directed towards the quartz. On the other hand when the spacing layer is filled with a medium of high refractive index, or when the Si-NCs layer is directly placed on top of the IBC cell, approximately 60% of the emission is directed towards the silicon which, ultimately, results in an increased J_{sc} . According to the Purcell effect, the LDOS is influenced by the refractive index so that a larger number of available electromagnetic modes in which photons can be emitted exist in the material with the higher refractive index. This effect (13–15]. Here, we demonstrated that it is essential to drive the luminescent downshifted emission efficiently into the active region of the solar cell.

4. Conclusions

In conclusion, we demonstrated a cost-effective implementation of the luminescent downshifting effect in IBC silicon cells. A best efficiency of 18.8% with an absolute enhancement of 0.8% with respect to reference was observed. The engineering of the LDOS in light harvesting has to be further investigated and maybe related to other features of LDOS, such as the possibility to exceed the simple ray optic light trapping limit [7], to further increase the cell efficiency.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.solmat.2014.09.007.

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