Hindawi Publishing Corporation
International Journal of Photoenergy
Volume 2013, Article ID 480634, 6 pages
http://dx.doi.org/10.1155/2013/480634

Research Article

Numerical Simulation of Luminescent Downshifting in Top Cell of Monolithic Tandem Solar Cells

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Received 20 May 2013; Revised 8 July 2013; Accepted 10 July 2013

Academic Editor: Gaetano Di Marco

The increase in the conversion efficiency of monolithic tandem solar cells is limited by the short-circuit current density matching between the top and the bottom cells. Generally, the top cell presents the lowest current in the two subcells. In this paper, in order to increase the short-circuit current density in the top cell, we present a theoretical survey of the luminescence downshifting (LDS) approach for the design of monolithic tandem solar cells. The photovoltaic (PV) glass encapsulation material is replaced with a polymer material of polymethyl methacrylate (PMMA) type which is doped with diverse kinds of organic dyes. The performance of the n-p-p+ GaInP structure has been simulated as a function of the organic dyes. Gains achieved for the short-circuit current density and conversion efficiency are, respectively, 13.13% and 13.38%, under AM1.5G illumination spectra.

1. Introduction

Multijunction solar cells can increase the efficiency of the cell by introducing another semiconductor able to reduce losses in high energy photons. There are three approaches, monolithic cells, mechanically stacked cells, and spatial-configuration approaches [1]. The monolithic solar cells present an elegant approach in reducing the number of processing steps by using a single substrate, but it requires two main conditions: first, the thin layers of epitaxial semiconductors must have closer lattice constant parameters, and second, we must have an adequate current matching between subcells. However, in this series connection, the subcell with the lowest photocurrent, limits the current generated by the full device structure [1, 2]. To fulfill the second criterion, we must adjust the top cell thickness because it presents lower short-circuit current density compared with the bottom cell of the tandem structure. Generally, we adjust short-circuit current density by adjusting the thickness of the top cell's base layer [2].

In 1990, under one-sun air mass 1.5 global radiation (AM1.5G) condition, efficiencies greater than 27% were achieved by changing the top-cell thickness to ensure current matching [3, 4]. However, increasing the thickness of the base layer in the top cell leads to an increase in absorption losses, the radiances in tandem solar cells are attenuated exponentially with respect to the thickness of layer.

In the present study, we propose an alternative method to increase the short-circuit current density in the top cell, based on the manipulation of the incident spectrum before its absorption by the solar cell; the idea is to substitute PV glass encapsulation materials with a thin layer of polymer material PMMA doped with optically active components. It has been shown in previous works that this approach results in performance improvement on some single junctions (CdTe, mc-Si, c-Si, GaAs, and CIGS) [5–7]. Besides, it reduces the cost and weight of the final PV module.

2. Materials and Methods

2.1. Luminescence Downshifting Principle. Originally, luminescent Downshifting (LDS) was first proposed in the late seventies by Hovel et al. [8]. The LDS approach is based on shifting parts of high energy photons from the ultraviolet (UV) region where the quantum efficiency (QE) of the cell is poor to the visible and infrared regions where the QE is

Table 1: Optical properties of diver's kinds of dyes used.

Dyes	Absorption range (nm)	Emission range (nm)	Max abs. (nm)	Max emis. (nm)	LQE (%)
Violet 570	300–410	400–520	378	413	94
Yellow 083	350–500	460–600	476	490	99
Orange 240	440–550	520–650	524	539	100

higher. A thin layer of PMMA doped with organic dyes plays the role of a photon converter; it absorbs UV photons before they are absorbed by the encapsulated material and emits them in a longer wavelength. Figure 1 illustrates the concept of downshifting introduced by organic dyes on the AM1.5G solar spectrum [9]. Also, we see that the GaInP solar cell uses photon energies in the range between 300 nm and 660 nm; it has a significant visible spectrum and a poor sensitivity in the violet and blue regions [10].

For better matching between the LDS layer and the response of GaInP solar cell, organic dyes need to be selected to absorb photons at a short wavelength, where the GaInP cell exhibits low quantum efficiency, then reemits them at a longer wavelength where the solar cell exhibits a significantly better response.

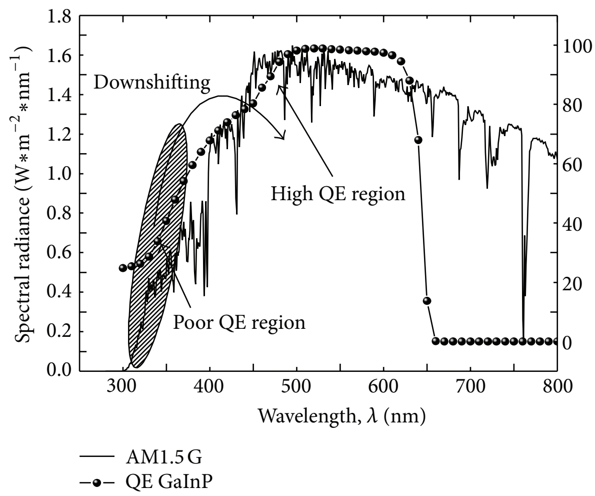


Figure 1: Solar spectrum AM1.5G, quantum efficiency of GaInP cell, and principle of downshifting.

2.2. Encapsulation Material and Luminescent Dyes. Polymethyl methacrylate (PMMA) is an excellent photovoltaic encapsulation material which was introduced recently in the manufacturing process of photovoltaic modules. It has a set of appealing mechanical and optical properties [11], in addition to its high transmittance spectrum along the region where the solar cell's response is high. PMMA is robust against heat treatments that the solar cells undergo during their manufacturing process; besides, it has a photostability extending over long periods of 20–25 years [10]. It is also recyclable and has an excellent stability against ultraviolet (UV) radiations [12].

In the present study, we will investigate the three fluorescent organic dyes (BASF Lumogen Violet 570 (V570), Yellow 083 (Y083), and Orange 240 (O240)) [13]. They are all made of napthalomide and perylene molecules, manufactured by BASF (Ludwigshafen, Germany). These organic dyes were studied in several papers of McIntosh et al. [12, 14]. They have many features; namely, they are cheap, photostable to UV, and easy to process in polymeric matrices, and they exhibit near-unity luminescence quantum efficiencies (LQE) [6]. The optical properties of dopants are listed in Table 1.

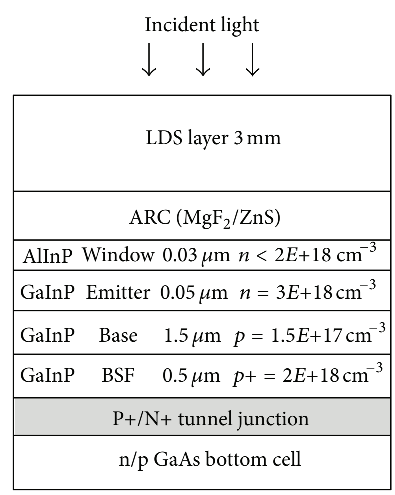


Figure 2: Schematic of a multijunction solar cell with LDS layer.

2.3. GaInP Devices. In this work, we have introduced an LDS layer on the top cell of the monolithic tandem solar cell studied by Takamoto et al. [21]. Figure 2 shows a schematic diagram of the tandem solar cell studied with LDS layer. The technological parameters for the different layers (thickness and doping level), used in this paper, are the same as those used by Takamoto et al. [21]. The top cell consists of a layer $p + Ga_{0.5}In_{0.5}P$ BSF, a base layer p $Ga_{0.5}In_{0.5}P$, an emitter $n + Ga_{0.5}In_{0.5}P$, and the window $n + Al_{0.52}In_{0.48}P$. The ZnS/MgF_2 antireflection coating (ARC) layer allows the reduction of the average reflectivity in the wavelength region between 400 and 900 nm to less than 2% [21]. The main parameters used in the calculations are shown in Table 2.

Simulations of the heterostructure were performed using the solar cells simulator SCAPS1-D (solar cell capacitance simulator in one dimension), developed at ELIS laboratory (Electronics and Information Systems) in GENT University, Belgium [22].

2.4. Simulation Methods. To study the gain in the efficiency of GaInP solar cells as a function of the organic dyes, we made

Table 2: Main material parameters used in the simulation.

Material	GaInP	AlInP
Band Gap (eV)	1.9 [15]	2.4 [1]
Electron affinity (eV)	4.1 [15]	4.2 [1]
CB effective density of states (cm^{-3})	1.3E + 20 [15]	1.08E + 20 [16]
VB effective density of states (cm^{-3})	1.28E + 19 [15]	1.28E + 19 [16]
Electron thermal velocity (cm/s)	1.00E + 6 [15]	1.00E + 7 [16]
Hole thermal velocity (cm/s)	1.00E + 6 [15]	1.00E + 7 [16]
Electron mobility (cm^2/Vs)	Varied [17, 18]	100 [16]
Hole mobility (cm^2/Vs)	40 [17, 18]	10 [16]
Lattice constant a (A°)	5.65 [15]	5.65 [15]
Absorption coefficients α (m^{-1})	Data from [19]	Data from [20]

a luminescent cascade (absorption and reemission) of photons so that a wide absorption can be reached. Several dyes can be mixed together within one layer in order to improve their absorption bandwidth, the Violet 570 absorption peak lies in the low QE region; however, it emits photons at wavelengths of Yellow 083 absorption range. This last emits photons at wavelengths of Orange 240 absorption range which in turn emits photon in the high QE region of the cell that ensures a better exploitation of the incident spectrum by the cell. Table 3 presents the three mixtures used in our study; the thickness of the PMMA used for the three samples is 3 mm; dyes' concentration was chosen to yield a peak absorption around 70%–90% in a 3 mm thick sample, typically the PMMA concentration is around 2-3 ppm (parts per million) [23].

The LDS layer is assumed to have complete absorption of all light incidents with wavelengths shorter than 400 nm. These dyes (Violet 570, Yellow 083, and Orange 240) were chosen because of their relatively high absorption coefficients and photoluminescent quantum yield (PLQY) [23].

When the structure (GaInP with LDS layer) is exposed to the incident solar spectrum $\varphi_s(\lambda)$, it is affected and modified by absorption and emission of photons in the PMMA mixed layer. The resulting spectrum $\varphi_{sae}(\lambda)$ is calculated from the amount of the absorbed and emitted photons. Furthermore, three quarters of the emitted photons are directed towards the solar cell, due to the internal reflection within the converter layer; the dye emission is isotropic [24].

The amount of photons absorbed depends on the thickness and the concentration of dyes in the LDS layer and is determined from the absorption spectrum of the dyes. The photon flux density decays exponentially after crossing a distance x in PMMA layer $\varphi(x,\lambda) = \varphi_0(\lambda)\exp(-\alpha(\lambda)\times x)$ where $\alpha(\lambda)$ is the absorption coefficient (cm^{-1}) of the LDS layer, and the exponential term is given by $\alpha(\lambda)\times x = \varepsilon_\lambda \times C \times D$, where ε_λ is the molar extinction coefficient ($M^{-1}\,cm^{-1}$), C is the concentration (M), and D is the thickness of film

Table 3: The three mixed samples of PMMA doped with organic dyes used in the present study.

Sample	Characteristic
S1	PMMA doped with Violet 570 dye
S2	S1 + Yellow 083 dye
S3	S2 + Orange 240 dye

(cm). In addition, the absorption is enhanced if the thickness of the PMMA and the concentration of the dyes are higher, besides, the amount of photons emitted in the infrared region $\varphi_e(\lambda)$ is calculated from the dyes emission spectrum, and the resulting spectrum $\varphi_{sae}(\lambda)$ serves as an input for the solar cell simulation models [24, 25]:

$$\varphi_{sae}(\lambda) = \varphi_s(\lambda) - \varphi_a(\lambda) + \varphi_e(\lambda), \quad (1)$$

where $\varphi_s(\lambda)$ is the incident solar spectrum, $\varphi_a(\lambda)$ the amount of photons absorbed by dyes introduced in PMMA layer, and $\varphi_e(\lambda)$ the amount of photons emitted by dyes introduced in PMMA layer.

The short-circuit current density (J_{sc}) of a solar cell is a function of the cell's quantum efficiency QE (λ) and the resulting spectrum $\varphi_{sae}(\lambda)$:

$$J_{sc} = q\int_{\lambda_1}^{\lambda_2} \mathrm{QE}(\lambda)\times\varphi_{sae}(\lambda)\,d(\lambda), \quad (2)$$

where q is the elementary charge and λ_1 and λ_2 define the range of the spectrum for which the J_{sc} is to be calculated.

It follows that, in order to increase the short-circuit current density in the cell, more photons must be shifted from the poor QE region to the higher QE region.

3. Simulation Results and Discussions

The performance of the GaInP solar cell was simulated without an LDS layer, and the obtained results were in accordance with those in the literature [21]. When an LDS layer is introduced on the top of the solar cell, organic dyes produce a substantial modification on the incident AM1.5G spectrum; they oblige the photons in the ultraviolet region to shift towards the visible region. The simulation is carried out for different numbers of organic dyes (S1, S2, and S3); for each case the effect on AM1.5G spectrum is shown in Figure 3.

SCAPS-1D simulations were carried out using the three samples of mixed dyes (S1, S2, and S3), using the resulting modified spectrum as an input for our simulation model. The variation of fill factor and open-circuit voltage with respect to the number of dyes added is presented in Figure 4 where it is clear that the open circuit voltage (V_{oc}) and fill factor (FF) do not change significantly. This is due to the fact that there is no change in the electronic properties of the semiconductor material or in the resistance of the device.

On the other hand, we see from Figure 5 that the variations in the short circuit current density and conversion efficiency are substantial. The increase in conversion efficiency is a result of the increasing current generation because

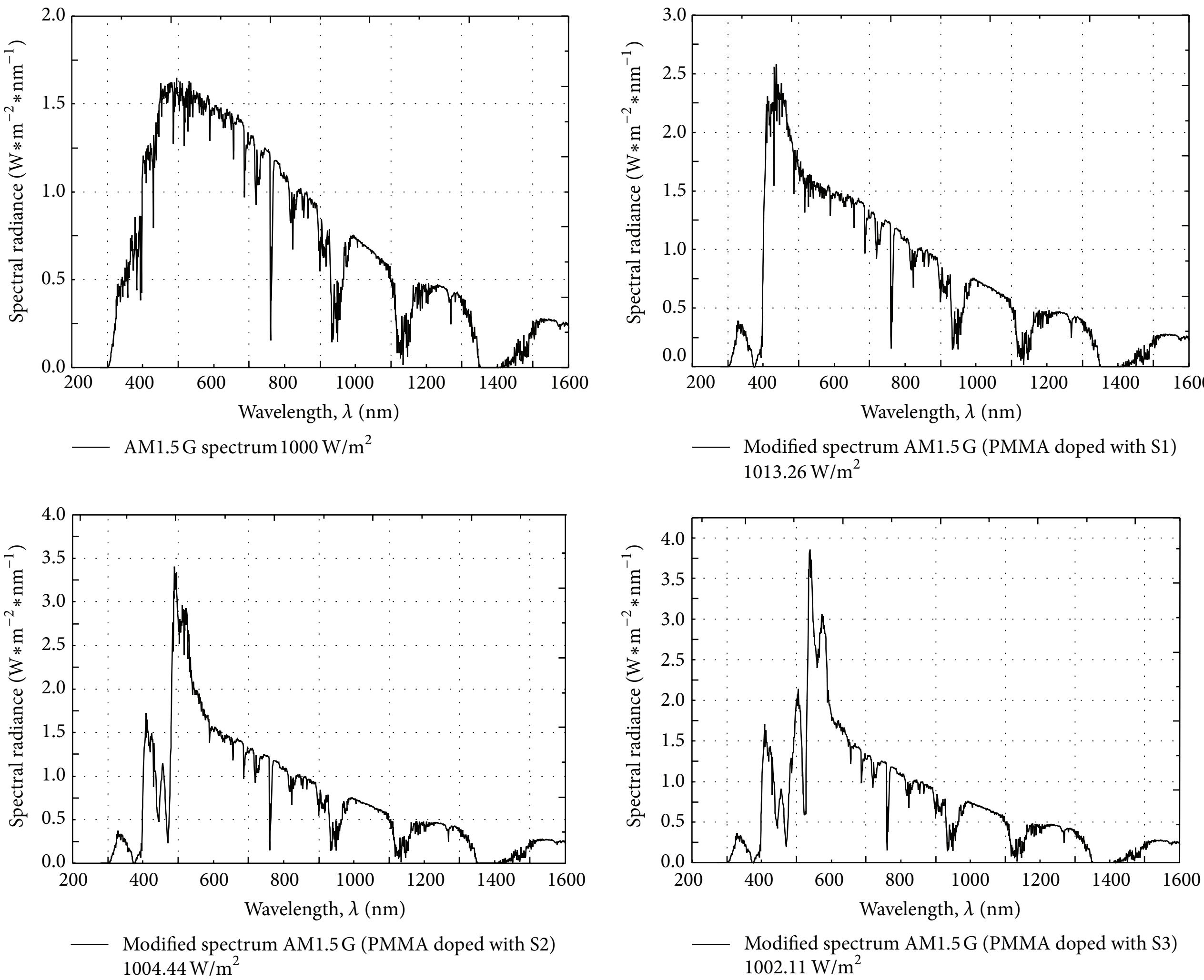


Figure 3: The luminescent downshift (LDS) effect on the AM1.5G solar spectrum.

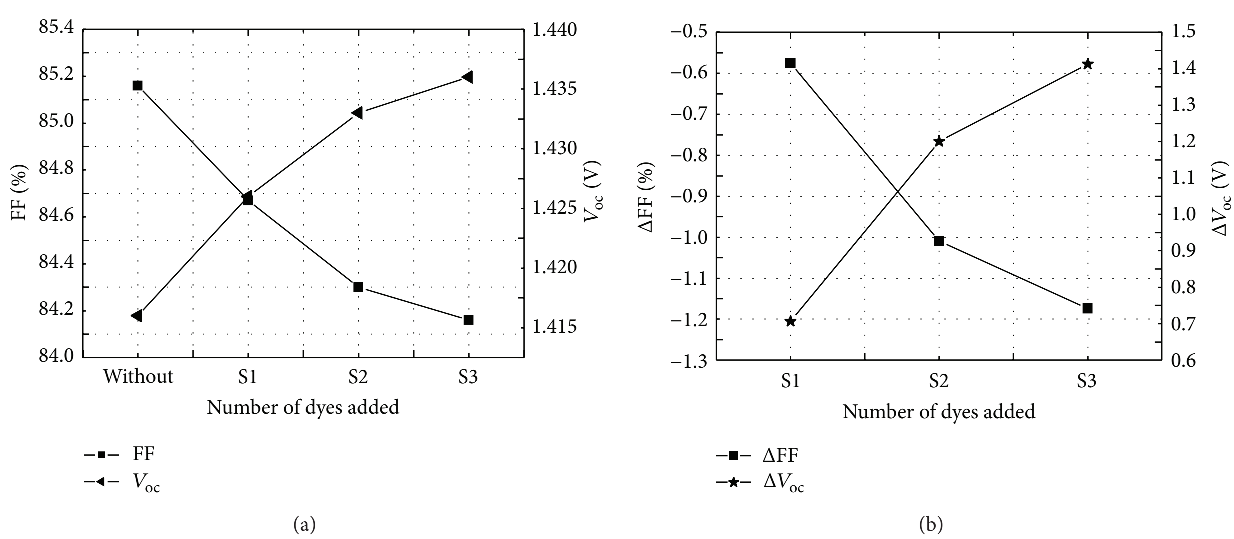
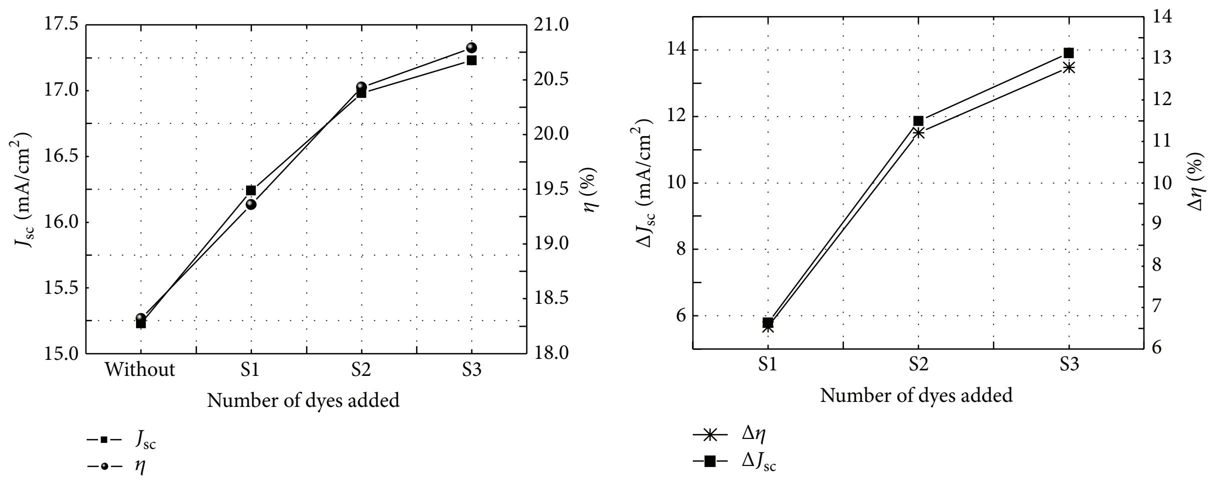


Figure 4: Simulation results of the variation of (a) fill factor and open-circuit voltage with the number of dyes added and (b) increase in fill factor and open-circuit voltage with the number of dyes added.



(a) (b)

Figure 5: Simulation results of (a) the short-circuit current density and conversion efficiency variation with the number of dyes added and (b) the increase in the short-circuit current density and conversion efficiency variation with the number of dyes added.

Table 4: Short-circuit current density and efficiency of the GaInP solar cell with and without LDS.

J_{sc} (mA/cm²) GaInP cell without PMMA	J_{sc} (mA/cm²) GaInP cell with PMMA doped (S3)	η (%) GaInP cell without PMMA	η (%) GaInP cell with PMMA doped (S3)	J_{sc} current improve (%)	Efficiency η improve (%)
15.23	17.23	18.32	20.79	**13.13**	**13.48**

the short-circuit current density varies proportionally with the quantity of photons shifted by the LDS layer.

The study of the improvements brought by the LDS layer on the GaInP solar cell, as a function of the number of dyes added, has shown that better results are achieved for the samples S1 and S2 (violet, violet, and yellow) with gains in short-circuit current density of 6.63% and 4.86%, respectively, whereas the addition of the third dye contributes only with 1.64% in the total increase. This is due to the fact that the QE of GaInP is poor in the absorption and emission spectrum of the two samples S1 and S2; hence, there is more photon transfer from UV and blue regions, where the collection probability of these photons is lower to the visible region, where the probability of collection is higher. Furthermore, when we add the third dye (orange 240) to S2, it induces absorption and reemission of photons in the region where the QE of the cell is already high (QE above 80%). So, there is less contribution in the collected current of the GaInP solar cell.

The simulated J-V characteristics of the GaInP structure with and without our specific downshift (PMMA doped with S3) are shown in Figure 6 where we observe an important increase in the short circuit current density and the cell's conversion efficiency. The gains in short-circuit current density and the conversion efficiency are summarized in Table 4.

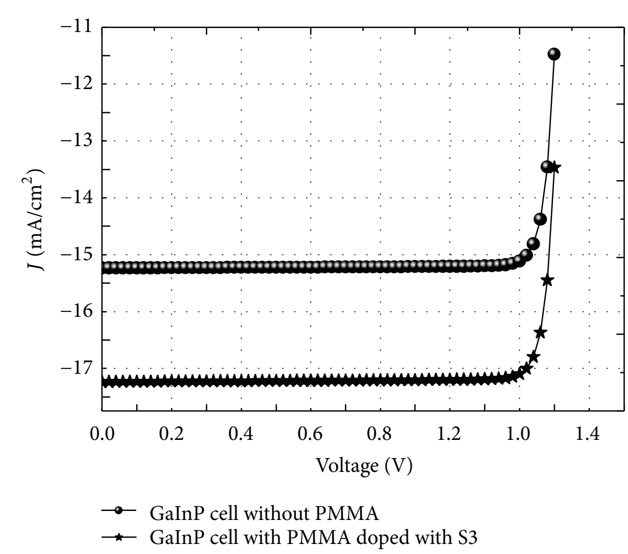


Figure 6: Simulation results of GaInP solar cell characteristics with and without LDS PMMA layer.

4. Conclusion

We proved, in this work, that the performances of the GaInP top monolithic solar cell are improved by introducing luminescence downshifting (LDS) layers. These performances have been simulated as a function of the mixture of the organic dyes (Violet 570, Yellow 083, and Orange 240). The simulation results have shown that, under the AM1.5G illumination spectrum, increases in the short-circuit current density and in the conversion efficiency of 13.13% and 13.48%

are, respectively, achieved by using an LDS layer doped by a mixture of the three dyes (Violet 570, Yellow 083, and Orange 240).

The two organic dyes Violet 570 and Yellow 083 have a great contribution in augmenting the efficiency of the solar cell compared to the Orange 240 dye; hence, they are more suited for GaInP solar cells with an LDS layer.

The use of an LDS layer allowed an increase in the efficiency of the GaInP top cell to values above 20%. Finally, in order to improve the solar cell performances, we plan in future works to study the behavior of the tandem solar cell with several dyes concentrations and obtain the optimum concentration corresponding to this structure.

Acknowledgment

The authors wish to thank Dr. M. Burgelman's group of Electronics and Information Systems (ELIS), University of Gent, for the SCAPS-1D program tool.

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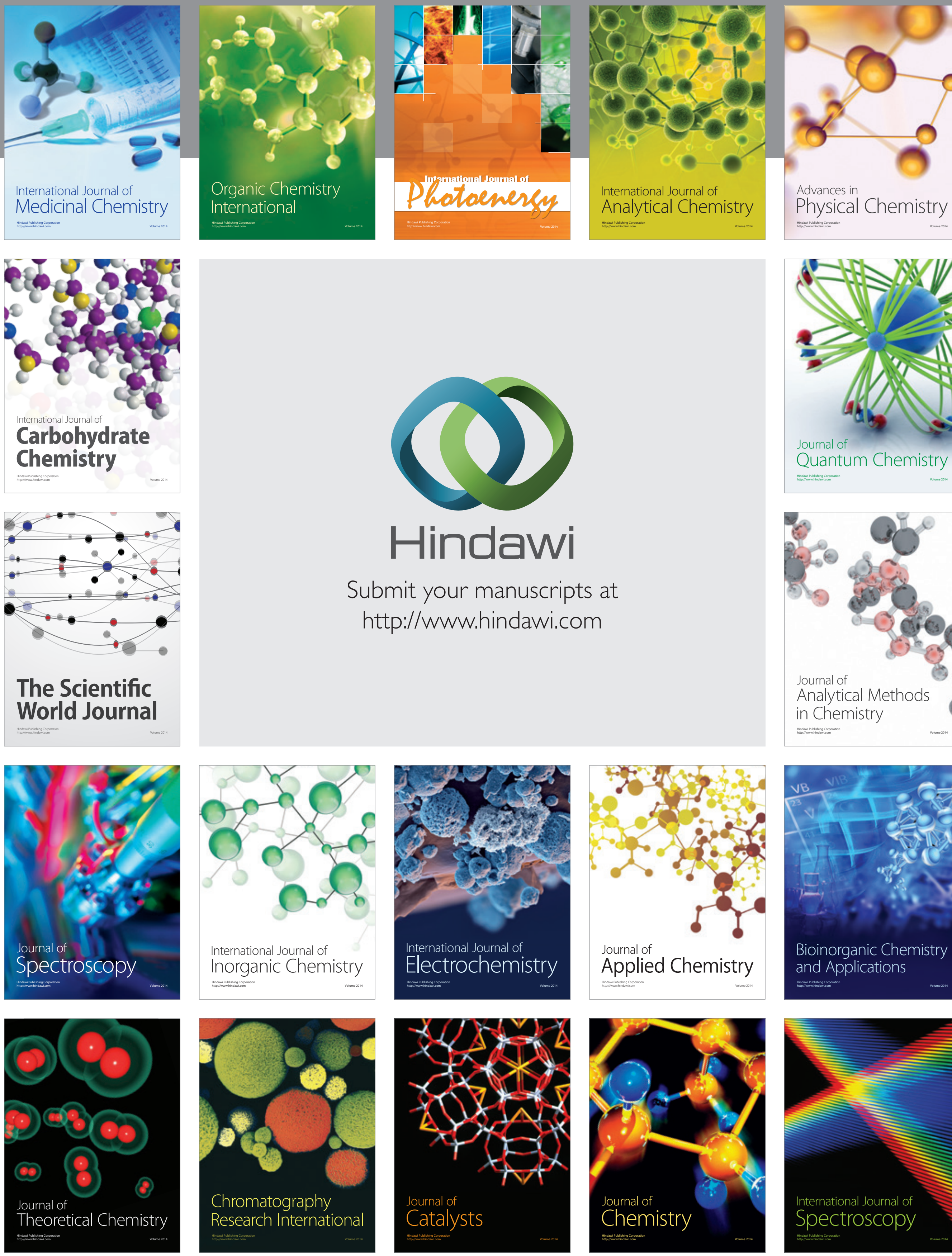
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