LUMOGEN VIOLET DYE AS LUMINESCENT DOWN-SHIFTING LAYER FOR C-SILICON SOLAR CELLS

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ABSTRACT: In this investigation Naphtalimide based Lumogen Violet organic dye [BASF] is characterized for inclusion in luminescent downshifting (LDS) layers. A PV device made up of an LDS layer of Lumogen Violet deposited on top of a crystalline silicon cell has been fabricated to improve its power conversion efficiency. External quantum efficiency measurements and outdoor tests for the PV/LDS devices are discussed. An analytical model was also developed to compare experiment results with the model predictions.
Keywords: luminescent down-shifting, spectral response, solar cell efficiency, External quantum efficiency

1 INTRODUCTION

Luminescent Down-Shifting (LDS) is a purely optical approach to increase a solar cell's ultra-violet/blue response by shifting short wave-length light to longer wavelengths where the external quantum efficiency (EQE) of solar cell is higher [1-6]. The downshifted photons have wavelength which may better match the photosensitivity spectral response of the solar cell as illustrated in Figure 1. In the device, the luminescent materials convert the high energy photons to lower energy before the interaction with the solar cells occurs [7-10].

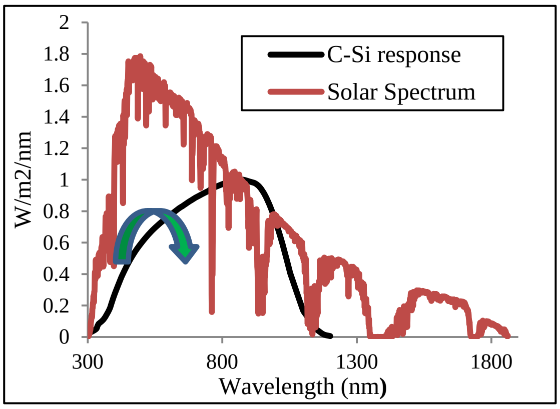

Figure 1: Luminescent down–shifting process to increase solar cell active range and efficiency. High energy photons are re-radiated at a longer wavelength, better matching the photosensitivity spectral response of the c-Si solar cell.

2 EXPERIMENTAL

2.1 LDS LAYERS AND DEVICE FABRICATION

Naphtalimide based Lumogen Violet organic dye [BASF] was used for inclusion in LDS layers. The LDS layers were prepared by dissolving the Violet dye in PMMA (Carl Roth GmbH+Co.KG) and Epoxy resin (ABL Resin & Glass, UK) solutions (1mg/ml in each case). The dye was first dissolved in 0.5g Toluene, added to the PMMA and Epoxy solution, and stirred for 45 minutes resulting in homogeneous solutions. Uniform thicknesses were achieved by drop casting the solutions onto glass plates.

The Lumogen Violet dye was selected as it has a high absorption coefficient, is relatively easy to process with polymers, and was found to have high LQY up to 99% in solution [11]. PMMA and Epoxy resin LDS layers of 0.26mm and 1.81mm thickness, respectively, were obtained. Mono-crystalline silicon cells (2x2 cm, Sunrydz, Germany) were used for assessing the downshifting effect of the Lumogen Violet in the PMMA and Epoxy host materials. The prepared LDS layers are cut to 20x20 sizes and attached to the PV cells with a thin layer (<100 microns) of epoxy, ensuring a good interfacial contact between cell and LDS layer without any air-gap present. In the following, the EQE measurements and outdoor tests was measured for two Si cell devices, one with a blank PMMA layer and the second one with an active LDS layer of Lumogen Violet/PMMA. The LDS layer of Epoxy was discarded due to the low quantum yield measured by the author in a previous work [11].

2.2 EXTERNAL QUANTUM EFFEICNCY

The EQE is the ratio of the number of charge carriers that are collected by the solar cell to the number of photons of a given wavelength entered into the solar [12]. The QEX10 Quantum Efficiency (PV Measurements, Inc, USA) was used to measure the EQE curves of the silicon cell/LDS device [13]. It is a spectral response and incident photon conversion efficiency based measurement system which uses a xenon arc lamp source, monochromator, filters and reflective optics under bias light. The monochromatic beam area is 1 cm^2 and directed at the centre of the cell as shown in Figure 2.

Figure 2: Si cell encapsulated with an LDS layer of Lumogen Violet/PMMA.

2.2 ANALYTICAL MODEL

An analytical model was developed to calculate the short circuit-current (Isc) of the silicon cell with a) blank PMMA layer and b) Lumogen violet/PMMA. In the model, the short circuit-current, I_{sc}, is given by [12];

$$Isc = \int E.\ SR\ d\lambda \qquad (1)$$

where E is the measured incident spectral irradiance for the solar simulator given in $Wm^{-2}nm^{-1}$. SR is the spectral response in AW^{-1} of the cell which gives a ratio of the photocurrent generated by the solar cell to the power incident on the solar cell at each wavelength. The spectral response can be determined from the measured EQE by [12];

$$SR = EQE.\frac{q\lambda}{hc} \qquad (2)$$

where q is the electron charge, λ is the wavelength, h is Planck's constant and **c** is the speed of light.

2.3 OUTDOOR TESTING

Outdoor characterization of the solar cell was developed and located on the roof top of Dublin Institute of Technology. It consists of two Kipp and Zonen CM-6b pyranometers aligned side by side to measure the Global radiation (Gh) and a EKO MS 710 spectroradiometer to record the solar spectrum from 337nm to 1100nm. A data logging system using a Delta T DL2e included in the setup to permit recording of values on a minute by minute basis. Also a horizontal platform adjacent to the pyranometers hosts the solar cell and a Keithley 2400 souce measurement unit was used to perform a voltage sweep on the solar cell. The four point probe (Kelvin) method was used to determine the corresponding current, yielding the I-V curve for the solar cell. A Labview interference was used to control the settings and the performance characteristics are derived from the I-V curve including the maximum power point (Pmax), fill factor (FF), short circuit current (Isc) and open circuit voltage (Voc). Typically three sweeps per minute are recorded and hourly averages of the global radiation and IV characteristics are used to calculate the efficiency (**η**) of the solar cell. The uncertainty in the efficiency of all outdoor measurements was calculated to be less than ±0.39% (absolute), using the Kline-McClintok method [14].

3 RESULTS AND DISCUSSION

In Figure 3 the EQE measurements for LDS layer of Lumogen Violet/PMMA- black dots and blank layer of PMMA- red dots is presented. An expanded view for the enhancement is shown in Figure 4. The EQE results showed there is an enhancement achieved when an LDS layer of Lumogen Violet/PMMA was used. The enhancement was noticeable for wavelength where violet is absorbing, 290-380 nm and it was calculated by integrating the area under the EQE curve to be 1.5%. The analytical model uses equation 1 to calculate the short circuit-current of the c-Si. The spectral response of the cell was calculated from equation 2 using the EQE that was measured in section 2.2 and presented in Figure 3. An increase of 2% in the short in the short circuit-current is predicted with this model for the c-Si cell when an LDS layer of Lumogen Violet is used. We would therefore expect the outdoor measured efficiency enhancement to be of this order.

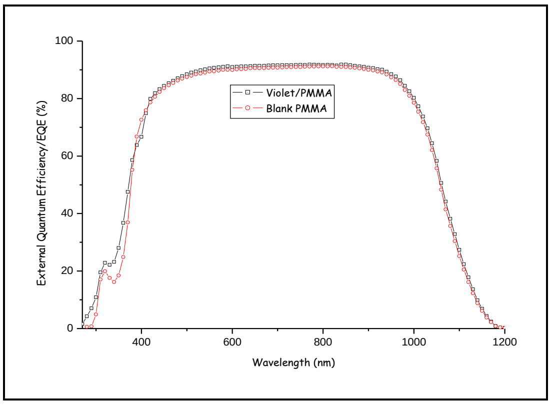

Figure 3: Comparison of EQE curves for Si cells encapsulated with Violet/PMMA layer (black dots) and blank PMMA layer (red dots).

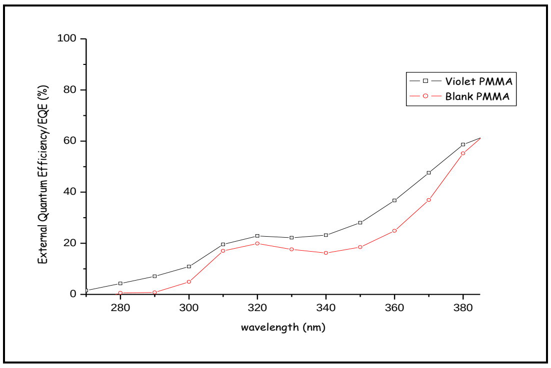

Figure 4: An expanded view for Figure 3 showing the enhancement of LDS is visible for wavelength where violet is absorbing (290-380 nm).

Table 1: I-V characteristics for c-Si solar cell with LDS layer of Violet/PMMA.

Date	Clock Time (BST)	η (%)	FF	Isc (mA)	Voc (V)
13 August 2012	10h	15.7	0.70	78.2	0.58
	11h	15.7	0.70	72.5	0.57
	14h	14.0	0.68	87.6	0.56
14 August 2012	10h	15.2	0.68	83.9	0.56
	11h	14.7	0.68	90.8	0.55
	12h	14.6	0.68	105.6	0.57
	14h	14.7	0.68	94.3	0.57
	15h	20.0	0.70	80.5	0.57
	16h	11.9	0.73	46.7	0.55
15 August 2012	11h	13.8	0.69	9.21	0.52
	15h	15.7	0.70	37.7	0.57
	16h	14.5	0.70	43.5	0.57
AVERAGE		15.1	0.69	69. 3	0.56

A comparison between output parameters recorded from the outdoor tests for the silicon cell with the LDS layer of Voilet dye and blank PMMA are presented in table 1 and table 2.

Table 2: I-V characteristics for c-Si solar cell with blank/PMMA layer

Date	Clock Time (BST)	η (%)	FF	Isc (mA)	Voc (V)
16 August 2012	12h	13.5	0.69	25.0	0.55
	13h	14.3	0.68	68.7	0.57
	14h	14.2	0.67	81.0	0.57
	15h	14.1	0.68	42.9	0.56
17 August 2012	15h	17.8	0.69	46.3	0.56
	16h	13.9	0.66	82.8	0.56
20 August 2012	13h	13.0	0.65	102.0	0.55
	14h	13.0	0.65	93.4	0.55
AVERAGE		14.2	0.67	67.8	0.56

The outdoor measurements were taken over aperiod of days and the tabulated data is presented in hourly averages. The measure of performance, efficiency of the solar cell, was determined using the average of the hourly efficiency data. The c-Si cell with LDS layer of violet/PMMA yielded an increase of 0.83% (absolute) in the efficiency of the solar cell compared to the c-Si solar with blank/PMMA layer. Furthermore, considering the short circuit-current of the solar cell relative to the level of global radiation (mA/W/m^2), the violet/PMMA cell showed an increase of 3.4% in the short circuit-current compared to the blank/PMMA cell.

4 CONCLUSION

External quantum efficiency measurements and outdoor tests have showed an increase in the short-wavelength response of the silicon solar cell was achieved due to the presence of Lumogen Violet dye. The Isc enhancement calculated with the analytical model yields good agreement with the outdoor measured enhancement. Further tests with more samples will be carried out in a future work where samples will be characterized simultaneously over a longer test period.

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