Monte Carlo Ray Tracing Modelling of Multi-Crystalline Silicon Photovoltaic Device Enhanced by Luminescent Material

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***Abstract* — The photovoltaic (PV) optical losses decrease the number of the collected photons resulting in decreasing the total PV conversion efficiency. One solution to increase the external quantum efficiency (EQE) of PV is using luminescent materials which can be applied by either coupling a luminescent down shifting (LDS) thin film to the PV top surface or doping the PV cell encapsulation layer with luminescent materials. In this paper, a Monte Carlo ray tracing (MCRT) algorithm has been developed to predict the EQE and current density of a device consisting of a multi-crystalline Silicon (mc-Si) PV solar cell in which the pre-existing poly-ethylene vinyl acetate (EVA) encapsulation layer has been doped with Lumogen-F violet 570 dye. The luminescent material down shifted the input radiation spectrum to the region where the PV cell has relatively high efficiency. Modelling and experimental results were in close agreement. EQE of the LDS/PV solar cell was enhanced by 15% and solar cell efficiency increased from 14.93% to 15.07%. The current density (J_{SC}) of the bare cell increased from 31.30 mA/cm^{-2} to 31.38 mA/cm^{-2} when the LDS device was attached.**

Keywords: Luminescent material, Monte Carlo ray tracing algorithm, PV, EQE.

I. Introduction

The optical losses in PV solar cell are from the absorption and reflection of the PV top glass, encapsulation and anti-reflective coating [1, 2]. To evaluate the performance of PV solar cells in each wavelength region, EQE is measured which is the ratio of the number of collected electrons to the number of incident photons [3-9]:

$$EQE(\lambda) = me(\lambda)/\, mp(\lambda) = \; IQE(\lambda) \times (1 - R_{PV}) \qquad (1)$$

Where $me(\lambda)$ is the number of electrons generated by the PV, $mp(\lambda)$ is the number of photons striking the PV solar cell at each wavelength, $IQE(\lambda)$is the internal quantum efficiency and R_{PV} is the probability of reflectance for the PV solar cell [10]. LDS thin film shown in Fig. 1, is a low cost technique to improve the efficiency of PV solar cells, by energy down-shifting the input solar radiation spectrum to the high-efficient region of PV cells [11-13].

In this paper, a MCRT algorithm is developed and used to model a device in which the EVA encapsulation layer of a mc-Si PV solar cell is doped with Lumogen-F violet 570 dye (BASF) [13]. The device was modelled and characterised under AM1.5 global solar radiation. Results were obtained and validated by comparing them with the experimental outcomes.

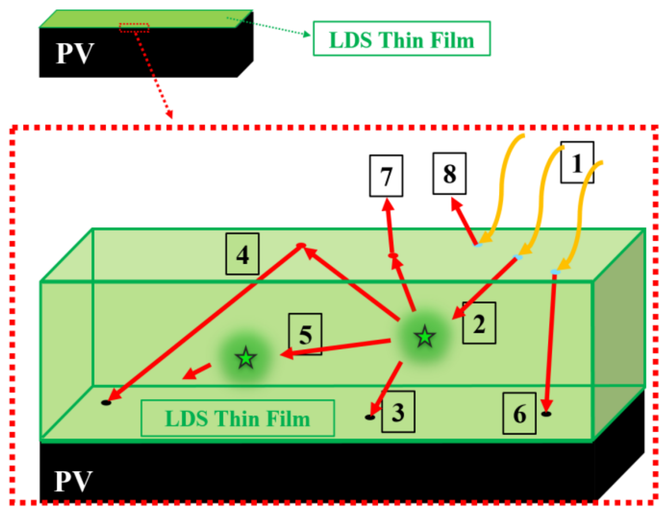

Fig. 1. Configuration of LDS thin film which shows: 1- incident ray strikes the LDS, 2- absorbed by luminescent material and emitted at longer wavelength. The emitted ray is either 3- reaches the PV cell directly or 4- it is wave-guided to the PV cell by total internal reflection or 5- re-absorbed by other particles, losses some part of its energy and re-emitted with less energy. 6- Some rays directly reach the PV cell without red-shifting. The losses include: 7- escape cone loss and 8- front surface reflection. Note that, attenuation and scattering losses of host material have not been shown here

II. MCRT Algorithm and Development

In the developed MCRT model, the device is radiated by a number of incident rays and the algorithm estimates the fate of each ray by considering the probability of optical events (such as reflection, refraction, absorbing, scattering, attenuating, wave-guiding and transmitting) occurring. Monte Carlo [9, 14-16] has a statistical nature; therefore, by increasing the number of incident rays, the accuracy of the model improves. Each incident ray which is represented by a vector and wavelength, is traced through the device to determine its fate [17]. At the intersection point of the incident ray and device, the reflection and refraction probabilities are calculated based on Snell's law and Fresnel equation [9, 18]. The refracted ray may be attenuated or scattered by the host material. Furthermore, it may be absorbed by the luminescent material. Absorption is obtained from Beer Lambert law [2, 8, 9]:

$$Tran = \; 10^{-A} = \, e^{-\tau} \qquad (2)$$

Where A is the absorbance and $Tran$ is the value of transmittance of the material. $\tau = d.\alpha_{Abs}$ is the optical depth (OD), α_{Abs} is the absorption coefficient and d is the thickness. The absorbed ray may be emitted based on the value of the Quantum Yield (QY) and the emission spectra of the luminescent material. During transmission, the behavior of rays is described by total internal reflection (TIR) phenomenon where the ray may strike other surfaces and if its incident angle is less than the critical solid angle θ_c of the medium, it will exit the device and lost as escape cone loss.

III. Results and Discussion

The specifications of the selected LDS/PV device [13] is presented in Table I. The device is a 77 × 77 mm including the EVA encapsulation layer with refraction index (η) of 1.51 and 0.5 mm thickness covered by 3.3 mm glass with η = 1.5. The absorption and emission spectra of the doped luminescent material (OD = 3 and QY = 90%) can be seen in Fig. 2.

TABLE I
CONFIGURATION OF THE LDS/ PV DEVICE [13]

Prosperities	Encapsulation Layer	Top Layer
Host Material Type	EVA	Glass
η	1.51	1.5
Length (mm)	77 mm	77 mm
Width (mm)	77 mm	77 mm
Thickness (mm)	0.5 mm	3.3 mm
Used Luminescent Material	Lumogen-F violet 570 dye	-----
QY of Luminescent Material	90% (100 ± 10%)	-----

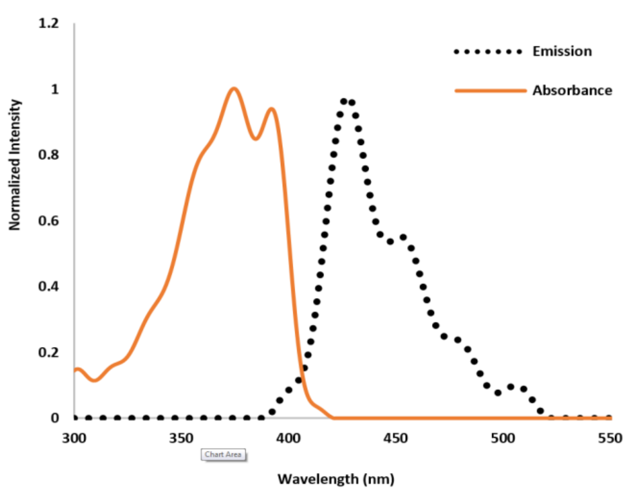

Fig. 2. Normalized emission and absorbance spectra of Lumogen-F violet 570 dye used for the enhancement of mc-Si PV solar cell.

The developed MCRT model was run under AM1.5 global solar radiation. Fig. 3 shows the visual structure during the simulation process under only 100 rays. As is seen, most of the rays are directed to the PV (the black plane at the bottom of the structure) while some of them are lost as heat in the top layers.

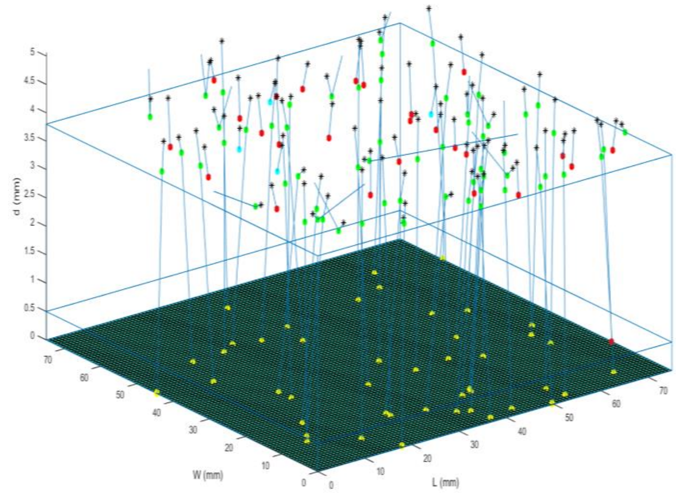

Fig. 3. Visual presentation of LDS/PV solar cell under simulation of 100 rays (Black plane: PV cell, Black spots: the ray sources, Red spots: thermal losses, Yellow spots: rays reaching the PV cell, Cyan spots: escape cone losses)

Table II shows the statistical results achieved by MCRT when the enhanced device is radiated by 1,000,000 rays. Around 18% of rays were reflected from the top surface due to the mismatch of the refraction indices of air and the glass layer. The rest of the rays were refracted (~83%) into the structure where around 7% of them were lost due to the loss mechanisms (including escape cone and thermal losses such as attenuation, scattering and reabsorption losses). The rest of the rays (~76%) were detected by the PV solar cell. The modelling and reference results for J_{SC} are closely matched. Due to using LDS layer, the current density (J_{SC}) was increased from 31.30 to 31.38 mA/cm^{-2} and resulted in increasing the solar cell efficiency from 14.93% to 15.07%.

TABLE II
STATISTICAL RESULTS ACHIEVED BY THE MCRT MODELLING

Parameter		Quantity
Reflected (%)		17.29
Refracted (%)		82.71
Thermal Loss (%)		0.15
Escape Cone Loss (%)		6.11
Strikes the PV (%)		76.45
J_{SC} (mA/ cm^{-2}) (Bare PV)	Reference[13]	31.30
	31.33	
J_{SC} (mA/ cm^{-2}) (Enhanced PV Device)	Reference[13]	31.38
	31.37	

Fig. 4 compares the reference EQE of the bare mc-Si PV cell with both the modified EQE of the enhanced PV device and modelling results obtained. As is seen, the modelling and experimental spectra are in close agreement. Due to doping EVA with the violet dye, the EQE has increased from 25% to 35% at 300 nm and improved by 15% in the region between 300 to 400 nm where the dye has the most absorbance.

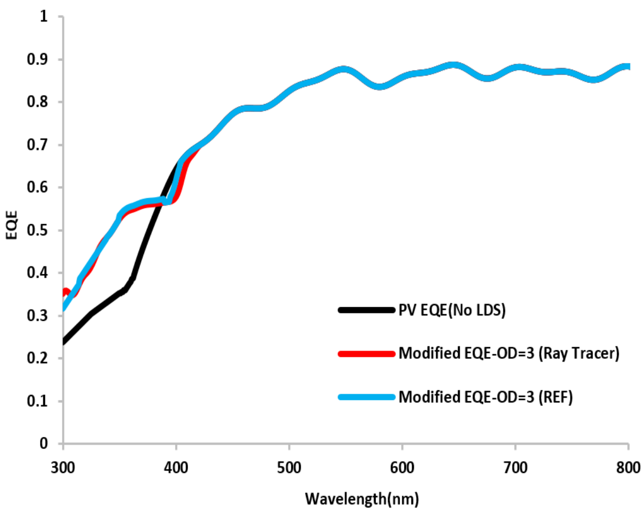

Fig. 4. Comparison of the modified EQE of the enhanced LDS/PV device with EQE of a bare PV solar cell

IV. CONCLUSION

In this paper, a MCRT algorithm was developed to model a 77 × 77 mm device with mc-Si PV solar cell which was covered with 0.5 mm EVA and 3.3 mm glass. The performance of the PV device was enhanced when the EVA layer was doped with Lumogen-F violet 570 dye. The value of optical depth was kept constant at 3 and the simulation was run with 1,000,000 rays (AM1.5 global solar radiation). The developed ray tracing algorithm estimated the EQE and current density of the PV device by detecting the fate of each incident ray while it was considering all loss mechanisms. The final modelling and experimental results were found in close agreement. The current density (J_{SC}) increased from 31.30 mA/cm^{-2} (for the bare PV) to 31.38 mA/cm^{-2} (for the LDS/ PV enhanced device). As a result, the solar cell efficiency increased from 14.93% to 15.07%. The EQE was enhanced by around 15% in the wavelength region between 300 nm to 400 nm.

V. ACKNOWLEDGMENT

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VI. REFERENCES

[1].R. Rothemund, *Optical modelling of the external quantum efficiency of solar cells with luminescent down-shifting layers.* Solar Energy Materials and Solar Cells, 2014. **120**: p. 616-621.

[2]. Efthymios Klampaftis, David Ross, Keith R. McIntosh, and Bryce S. Richards, *Enhancing the performance of solar cells via luminescent down-shifting of the incident spectrum: A review.* Solar Energy Materials and Solar Cells, 2009. **93**(8): p. 1182-1194.

[3]. Jenny Nelson, *The physics of solar cells*. Vol. 1. 2003: World Scientific.

[4]. Stuart R Wenham, *Applied photovoltaics*. 2012: Routledge.

[5]. Chetan Singh Solanki, *Solar photovoltaics: fundamentals, technologies and applications*. 2015: PHI Learning Pvt. Ltd.

[6]. Ewa Radziemska, *Effect of temperature on dark current characteristics of silicon solar cells and diodes.* International Journal of Energy Research, 2006. **30**(2): p. 127-134.

[7]. Cai Wen, Chao Fu, JinLong Tang, DeXiong Liu, SiFu Hu, and ZhiGang Xing, *The influence of environment temperatures on single crystalline and polycrystalline silicon solar cell performance.* Science China Physics, Mechanics and Astronomy, 2012. **55**(2): p. 235-241.

[8]. Mahfoud Abderrezek, Mohamed Fathi, Farid Djahli, and Mohammed Ayad, *Numerical Simulation of Luminescent Downshifting in Top Cell of Monolithic Tandem Solar Cells.* International Journal of Photoenergy, 2013. **2013**.

[9]. Derya Şahin and Boaz Ilan, *Radiative transport theory for light propagation in luminescent media.* JOSA A, 2013. **30**(5): p. 813-820.

[10]. WJ Yang, ZQ Ma, X Tang, CB Feng, WG Zhao, and PP Shi, *Internal quantum efficiency for solar cells.* Solar Energy, 2008. **82**(2): p. 106-110.

[11]. Hind Ahmed, *Materials Characterization And Plasmonic Interaction In Enhanced Luminescent Down-Shifting Layers For Photovoltaic Devices*. 2014, Dublin Institute of Technology.

[12]. HJ Hovel, RT Hodgson, and JM Woodall, *The effect of fluorescent wavelength shifting on solar cell spectral response.* Solar Energy Materials, 1979. **2**(1): p. 19-29.

[13]. E Klampaftis and BS Richards, *Improvement in multi-crystalline silicon solar cell efficiency via addition of luminescent material to EVA encapsulation layer.* Progress in Photovoltaics: Research and Applications, 2011. **19**(3): p. 345-351.

[14]. Steven L Jacques and Lihong Wang, *Monte Carlo modeling of light transport in tissues*, in *Optical-thermal response of laser-irradiated tissue*. 1995, Springer. p. 73-100.

[15]. David C Joy, *Monte Carlo modeling for electron microscopy and microanalysis*. 1995: Oxford University Press.

[16]. Derya Şahin, Boaz Ilan, and David F Kelley, *Monte-Carlo simulations of light propagation in luminescent solar concentrators based on semiconductor nanoparticles.* Journal of Applied Physics, 2011. **110**(3): p. 033108.

[17]. Andrew S Glassner, *An introduction to ray tracing*. 1989: Elsevier.

[18]. Hidetaka Ishihara, Som Sarang, Yen-Chang Chen, Oliver Lin, Pisrut Phummirat, Lai Thung, Jose Hernandez, Sayantani Ghosh, and Vincent Tung, *Nature inspiring processing route toward high throughput production of perovskite photovoltaics.* Journal of Materials Chemistry A, 2016. **4**(18): p. 6989-6997.