Chapter 59
External Quantum Efficiency Measurements and Outdoor Characterisation for PV Luminescent Downshifting Devices

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59.1 Introduction

As part of the European Union energy and climate goals, 20% of the final energy consumption should come from renewable technology, and by 2030 the target has been set to 27% [1]. Harvesting solar energy has the potential to reduce carbon emissions and to provide clean energy contributing to sustainable development. The solar spectrum received at the Earth surface covers a wide range of wavelengths from 290 nm to 3790 nm. In an ideal situation, the absorption spectrum of PV materials should perfectly match the entire solar spectrum in order to convert the maximum photons from solar radiation to electricity. However, there is a large mismatch between the solar emission spectrum and the absorption properties of the present PV materials. At short wavelengths, each photon has a large energy, and therefore the ratio of photons to power is reduced. Any energy in excess of the band gap energy of the solar cell materials is not utilised by the solar cell and instead goes to heating the solar cell and is therefore wasted [2, 3]. Loss mechanisms in photovoltaic represent a practical limit to the solar cell efficiency, and the potential remains to make a better use of the short wavelength radiation. In order for high efficiencies to be achieved in PV technologies, energy loss mechanisms must be reduced. Luminescent downshifting (LDS) layer is a method which aim to convert non-absorbable solar radiation in the UV (290–400 nm) into absorbable incoming

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radiation in the visible (400–700 nm) via florescence phenomena, hence increasing the solar optical response for short wavelength radiation [4–13, 15]. It has been proposed in the late 1970s when Hovel et al. realised that instead of concentrating sunlight high-energy photons could be converted to low energy to overcome the poor solar cell performance in UV, blue light. It involves a luminescent species that is applied in a transparent polymer/glass host material on top of the PV cell [7].

59.2 Experimental

59.2.1 LDS Layer Preparation and Device Fabrication

LDS layers with different concentrations (0.082, 0.44 and 0.170% w/w) of down-shifter compound were fabricated. Naphthalimide-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) solutions. The dye was first dissolved in toluene, added to the PMMA and stirred for 45 min resulting in homogeneous solutions. Uniform thicknesses of (100 ± 05 μm) were achieved by drop casting the solutions onto glass plates. Monocrystalline silicon cells (2×2 cm, Sunrydz, Germany) were used to assess the downshifting effect of Lumogen Violet in PMMA. LDS layer was attached to the c-Si cell using a thin layer (<50 μm) of epoxy as adhesive. A total of four devices were fabricated and are presented in Fig. 59.1. The performances of the c-Si cells, before and after the LDS encapsulation, were characterised outdoors, and the external quantum efficiency was measured. Results of both measurements are discussed below in details.

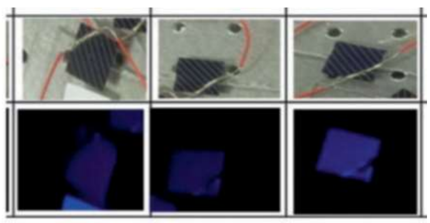
	Reference device	c-Si + Lumogen Violet LDS Devices		
#	C1	C2	C3	C4
Components	c-Si + Blank PMMA	c-Si + LDS (0.082%w/w)	c-Si + LDS (0.044%w/w)	c-Si + LDS (0.170%w/w)
Photo under room light				
Photo under UV light				

Fig. 59.1 Monocrystalline silicone cell with C1 blank PMMA C2, C3 and C4 Lumogen Violet/PMMA (concentrations of 0.082, 0.044 and 0.170% w/w) layer under room light and under UV lamp light

59.2.2 Absorption and Emission Measurements of LDS Layers

UV/Vis/NIR absorption spectroscopy was used to measure the absorption characteristics of the downshifting layers. The UV/Vis/NIR absorption spectrometer used was a Perkin Elmer Lambda 900. The emission spectra of the LDS layers were measured by optically pumping samples using a monochromated light source using a luminescence spectrometer Perkin Elmer LS55B.

59.2.3 External Quantum Efficiency Measurements

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 cell [14]. The QEX10 Quantum Efficiency (PV Measurements, Inc., USA) was used to measure the EQE curves of the silicon cell/LDS device. 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 center of the solar cells.

59.2.4 Outdoor Measurements of the LDS Devices and Performance Characteristics

Outdoor measurements were carried out on the four devices characterised over the same time period. IV performance characteristics in Table 59.1 were based on eight sets of hourly averages, recorded on January 3 and 4, 2014, on the Technological University Dublin roof setup. It consists of two Kipp and Zonen CM-6b pyranometers aligned side by side to measure the global radiation (Gh) and a EKOMS 710 spectroradiometer to record the solar spectrum from 337 nm to 1100 nm. A data logging system using a DeltaTDL2e included in the setup to permit recording of values on a minute-by-minute basis. Also a horizontal platform adjacent to the

Table 59.1 Average outdoor electrical characteristics

PV/ LDS	8Hrs AVG							
	LDS Devices	Pmax(mW)	Imp(mA)	Vmp(V)	FF	Isc(mA)	Voc(V)	Eff%
C1	cSi+ PMMA blank	7.39	16.64	0.43	0.67	19.44	0.55	13.00
C2	cSi+Lum V (0.082 w/w%)	8.45	17.93	0.47	0.75	19.72	0.56	15.00
C3	cSi+Lum V (0.044 w/w%)	7.21	16.05	0.44	0.70	18.15	0.55	13.00
C4	cSi+Lum V (0.17 w/w%)	6.87	15.34	0.44	0.71	17.18	0.55	12.00

pyranometers hosts the solar cell and a Keithley 2400 source 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. The setup permits comparison of a number of devices within the same time frames useful for comparison of hourly average performance characteristics. Electrical performance parameters such as Isc, Voc and FF are reported. 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 efficiency of the cell was calculated using the equation below:

$$\eta = \left(\frac{P_{max}}{Gh.A} \right) \times 100,$$

where P_{max} is the maximum power calculated in mW, *Gh* is the global radiation (the total short-wave radiation falling onto a horizontal surface) measured in Wm^{-2} and *A* is the cell area given in m^2. The *Gh* was measured 142.12 Wm^{-2} (1/7th of one sun), and the cell area was 0.0004 m^2.

59.3 Results and Discussions

Absorption and emission measurements of the layers are shown in Fig. 59.2. Absorbance of blank PMMA is also shown. It is clear that Lumogen Violet layers have retained their optical properties in PMMA films since the optical spectra are similar to those in solution.

In Fig. 59.3, the measured EQE of LDS devices with different compositions of Lumogen Violet and their equivalent c-Si cell with blank cover PMMA are presented. An expanded view for EQE in the UV region is shown in Fig. 59.4.

An enhancement has been observed in EQE for Lumogen Violet/PMMA LDS devices (C2 and C3) relative to the blank PMMA device (C1) while C4 has shown a decrease in EQE. The enhancement was noticeable for wavelengths where the violet dye is absorbing at 290–420 nm. Lumogen Violet devices have shown decrease in EQE from 380 nm to 420 nm; this is where the absorption and the emission spectra of Lumogen Violet are overlapping which might cause self-absorption. Also, the blank PMMA layer was found to have slightly absorbing between 300 nm and 370 nm which is penalising the c-Si cell efficiency at these UV wavelengths.

The average of 8-hour outdoor electrical characteristics of all PV/LDS devices are presented in Table 59.1.

The highest gain in overall efficiency η (%) was recorded in Lumogen Violet (C2, 0.082%) device which was 15% relative (2% absolute) higher than the corresponding reference cell C1 (η = 13%). Lumogen Violet (C3, 0.044%) device shows an increase of 0.5% while the Lumogen Violet (C4, 0.170%) device shows a decrease of 0.4% relative to the reference cell.

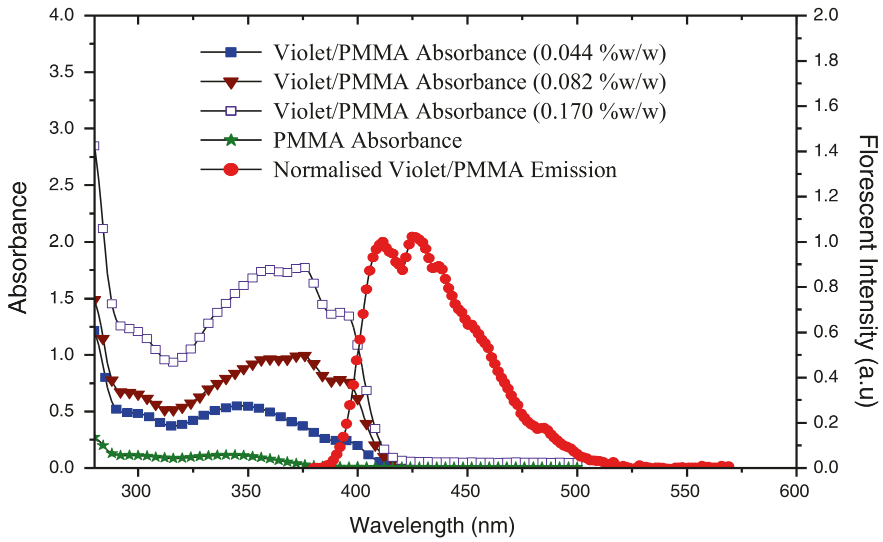


Fig. 59.2 Absorption and emission measurements of varying concentrations of Lumogen Violet in PMMA. Absorbance of blank PMMA is also shown

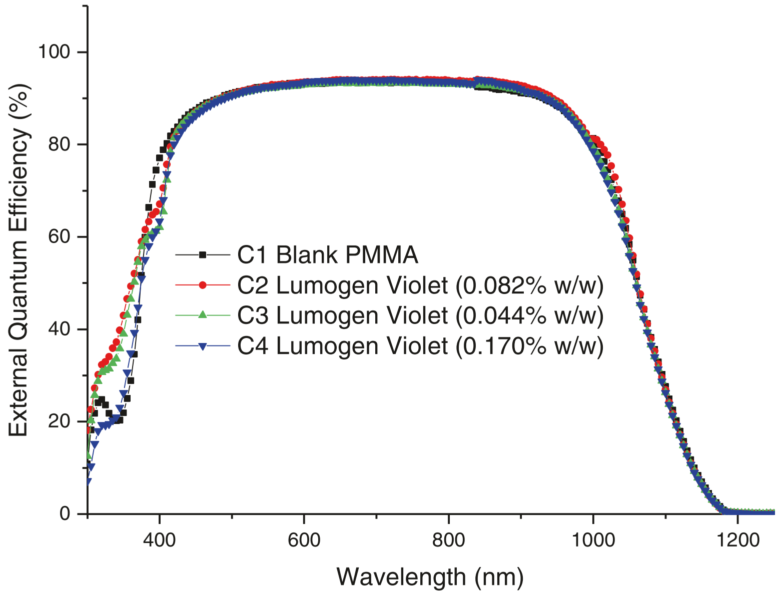


Fig. 59.3 Comparison of EQE curves for c-Si cells encapsulated with LDS layers of Lumogen Violet dye and PMMA. The EQE for the blank PMMA layer is also shown

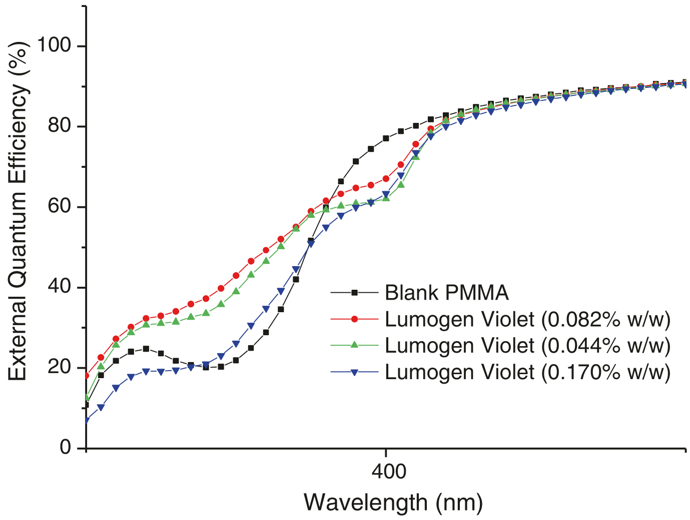


Fig. 59.4 An expanded view for EQE in the UV region comparing EQE curves for c-Si solar cells encapsulated with LDS layers of Lumogen Violet dye and PMMA. The EQE for the blank PMMA layer is also shown

The short-circuit current Isc measured for PV/LDS C2 device was 19% relative higher than the reference cell.

59.4 Conclusion

In this paper, Lumogen Violet downshifting organic dye has been characterised for its inclusion in luminescent downshifting (LDS) layers. Monocrystalline silicone (c-Si) solar cells were attached to Lumogen Violet LDS layer of different concentrations (0.082, 0.044 and 0.17% w/w) in PMMA films. The performance of the c-Si was characterised with and without LDS layers. An increase in EQE was demonstrated for c-Si devices with Lumogen Violet/PMMA layers of lower concentrations (4% for C2 (0.082% w/w) and 0.5% for C3 (0.044% w/w)), relative to the blank PMMA layer, while no enhancement was observed for LDS layer of higher concentration (C4, 0.17% w/w). The highest gain in solar cell efficiency was observed for the Lumogen Violet/PMMA with concentration of 0.082% w/w due to the action of the LDS layer compared to blank PMMA layer where a 15% relative increase has been measured. The short-circuit current, Isc, for this device was 19% relative higher than the reference cell.

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