Characterisation of a filter-based external quantum efficiency measurement system

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Abstract

Accurate assessment of external quantum efficiency provides information useful for understanding where losses in energy conversion efficiency occur in solar cells. These systems are typically designed to measure small areas only, which makes it impossible to measure the quantum efficiency of monolithically integrated modules and thus any effects due to interconnection cannot be assessed. A system for measuring spectral response has been designed and recently commissioned at CREST with a view to making measurements on larger areas. The external quantum efficiency of solar cells is calculated based around a series of narrow-band interference filters and homogenising optical elements that are able to provide a large-area, homogeneous, monochromatic illumination. In this paper the initial characterisation of the system will be presented. It is the intention to further improve the functionality of the system over the coming year and the planned enhancements will be discussed in light of their effects on measurement accuracy, in particular for devices such as dye cells and multi-junction cells which have more complicated electro-optical characteristics than basic silicon wafer cells.

Introduction

Measurement of the external quantum efficiency of solar cell devices requires a system capable of providing monochromatic illumination of well defined and reproducible wavelength and intensity. This is often achieved through the use of a grating monochromator in combination with edge-pass filters to block harmonics of the desired illumination wavelength. Whilst this approach readily provides closely spaced measurement points, it is challenging to scale up to large areas. An alternative approach is the use of band-pass filters, allowing a greater intensity of monochromatic light to be generated. This intensity potentially comes at the cost of reducing the number of measurement points available as an individual filter is required for each point and the range of filters available is far from continuous. However, sufficient filters are available to fulfil the requirements of the IEC standard governing solar cell spectral response measurements [1].

Figure 1 shows the schematic of such a filter based system that has been recently developed at CREST. A dual lamp source containing a xenon short arc lamp and a quartz halide lamp provides illumination from UV through to infrared wavelengths and this is monochromated by a series of filters housed in a motorised wheel assembly. The monochromated light is passed through a homogenising optical element that produces a square of illumination 150mm to a side at its focal length. This light may be chopped to allow detection of the small perturbation in photocurrent that this monochromatic illumination generates as it illuminates a solar cell. The system has further provision for providing both white light bias illumination and a bias voltage during measurement.

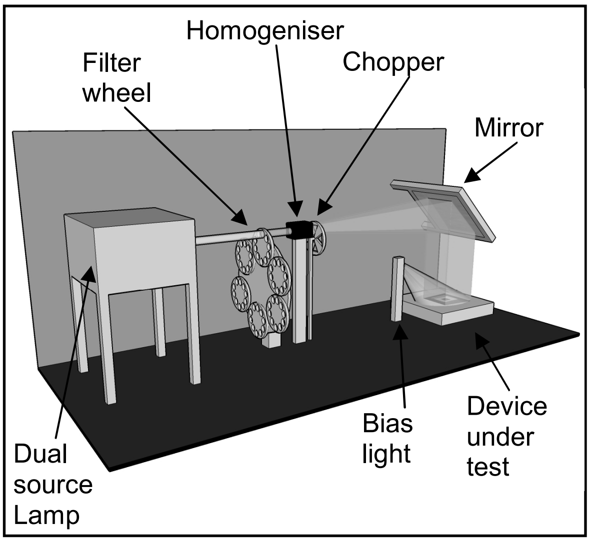

Figure 1: Schematic of the filter based EQE measurement system developed at CREST.

Results

A calibrated, two-colour photodiode from Hamamatsu has been used as a reference in the EQE system. The current response of this diode is measured to determine the photon flux as a function of wavelength and this is in turn used to determine the spectral response and EQE of a test cell from its current response. Figure 2 (top) shows the current response of the reference diode measured as both reference and sample. The xenon lamp was used to measure wavelengths below 750nm and the quartz halide lamp for wavelengths above this value. The two colour reference contains both c-Si and InGaAs photodiodes, stacked one above the other. The Si diode was used to measure at all wavelengths except those above 1090nm. Excellent agreement is observed between the two current response curves and this translates to less than 3% (relative) deviation between the measured EQE and the values calculated from the calibration data sheet spectral response (Figure 2, bottom). It is apparent from the current response measured using the halide lamps that a large contribution from the xenon lamp's output is mixed into the signal, in particular around the xenon emission peaks. This degree of accuracy can be reproducibly obtained when measuring the reference diode as the sample without moving it.

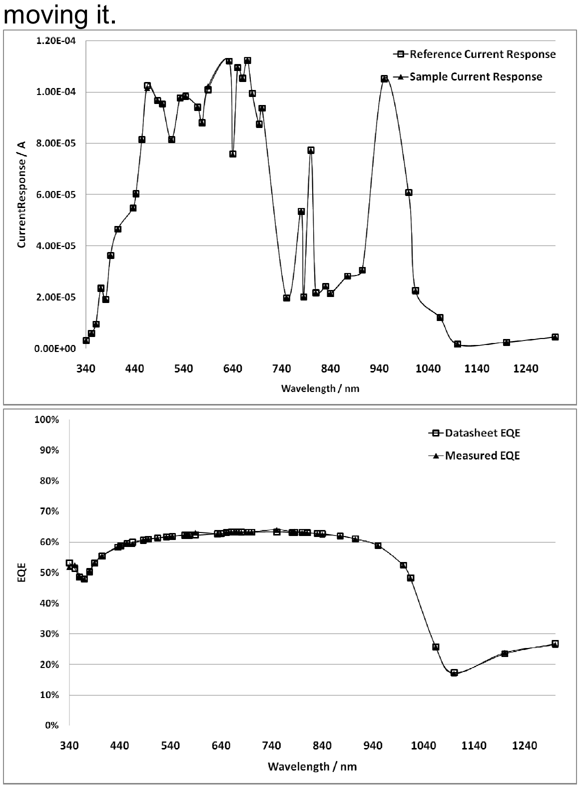

Figure 2: (Top) Current response of the reference cell measured as both reference and sample. (Bottom) Measured reference cell EQE compared to calibration file EQE.

In grating monochromator based systems, it is common for the illuminated area to be significantly smaller than the device under test so that the photon flux incident on the reference cell and cell under test are equal. The larger area system reported here instead relies on an optical homogeniser to provide uniform photon flux over the illuminated area, so that the entirety of devices larger than the reference may be measured. The degree of accuracy that is achievable with this system will therefore be influenced by the homogeneity of the illumination. Figure 3 shows a contour plot of the intensity in the focal plane of the homogeniser when a single LED is used as illumination source. This was mapped *ex situ* using a motorised x-y table with 5mm measurement grid size. The contours indicate 5% changes relative to the normalised peak intensity. The intensity is within 5% of the peak value for a square of area almost 100×100mm^2 and within 10% for a square of almost 130×130mm^2. The beam expansion and input geometry are slightly different in the EQE system, thus this is only an indication of the monochromated illumination homogeneity. However, it is a good indication that the target homogeneity of ±2% over a large surface will be achieved in the EQE system. Once the optical set-up in the EQE system is finalised, it will be possible to carry out an *in situ* measurement to confirm the illumination homogeneity.

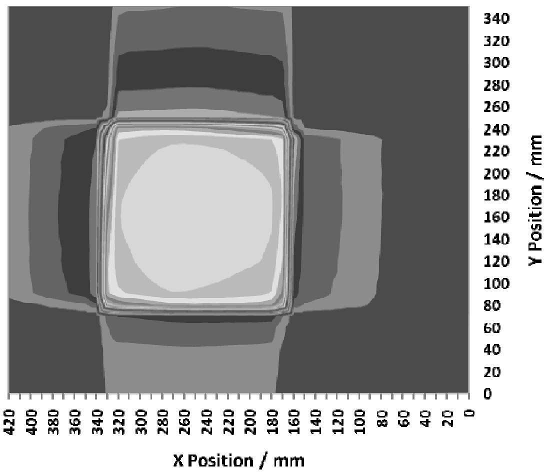

Figure 3: Normalised illumination intensity measured for an LED and the homogenising optic used in the EQE system. Contours are in 5% of peak signal.

Figure 4 shows the EQE curves measured for the reference when it was placed at the centre and corners of a square approximately 100mm to a side, centred on the centre of the illumintated area. Whilst less than 5% relative deviation is achieved for both measurements near to the centre of the illuminated area, the deviation near the corners ranges up to 10% for the points measured with the xenon lamp and up to 20% for those measured with the quartz halide lamp.

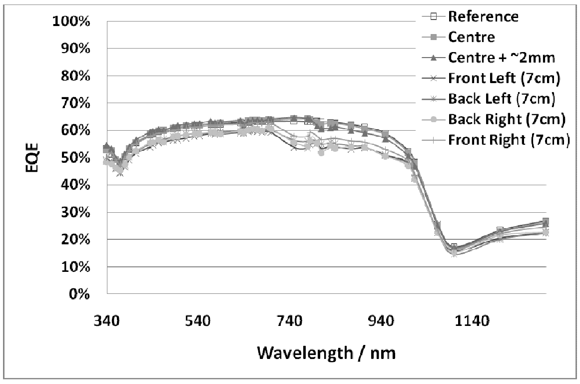

Figure 4: EQE curves measured at the corners and centre of a 100×100mm^2 area. The loss in intensity towards the corners is systematically different for the regions measured with the xenon and quartz halide lamps.

In order to understand the orgin of the differing degree of deviation between the points measured with the xenon lamp and those measured using the quartz halide lamp the intenisity of the output from the lamps was mapped across a target plane at a distance of approximately 70cm from the lamp. The normalised intensity distributions are shown in Figure 5 and it is clear that there is a slight misallignment between the output of the two lamps. The homogenising optic is very senstive to the angle of incidence of the source light and so it is considered likely that this misallignment is the source of the differing deviations observed in Figure 4. It will be possible to correct this misallignment by fine tuning the position of the mirror that selects between the lamps and this should greatly improve the homogeneity of the illumination and hence the large area measurement accuracy. The system will also benefit from the introduction of baffles to minimise stray light, whilst this currently has a small influence on the homogeneity of the illumination it prevents unchopped measurements from being made.

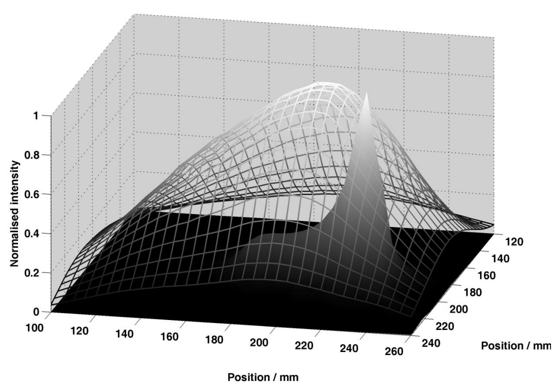

Figure 5: Relative intensity of xenon (solid) and quartz halide (mesh) lamps in target plane without homogenisation. A slight misalignment of the two lamps is evident and may explain the differences in shape between EQE curves measured at the corners of the illuminated area and the centre.

Due to the concerns about homogeneity discussed above, no quantitative EQE measurements have been made on cells other than the reference diode. However, to demonstrate the potential of the system normalised EQE curves were measured for several cell technologies and these curves are shown in Figure 6. The cell areas range from 10mm^2 for the copper indium gallium diselenide (CIGS) cell to 1380mm^2 for the a-Si cell. All of the measurements were made with no bias lighting at 175Hz chopping frequency and 0V bias. Whilst these curves are only indicative of the performance of the cells, they clearly show the different spectral features of the various technologies. Measurement of dye sensitized solar cell (DSC) EQE is known to be extremely sensitive to measurement conditions [2] and this is seen in Figure 6 by comparision of the curve measured with the conditions stated above and the curve measured at 65Hz chopping frequency under white bias lighting.

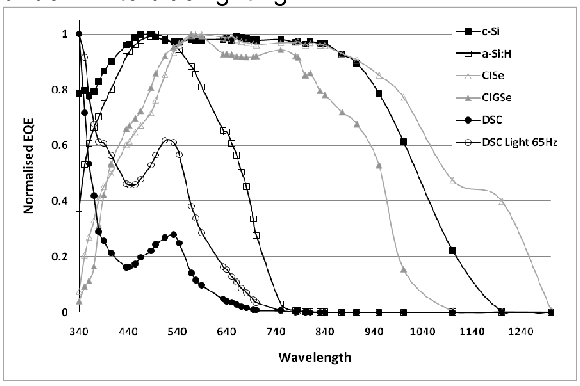

Figure 6: Normalised EQE curves for a range of cell technologies.

Conclusions and prospects

A filter-based system for measuring the spectral response and external quantum efficiency of photovoltaic devices has been developed at CREST and initial tests show that it is capable of achieving accuracies better than 5% (relative) on small areas. Characterisation of the system over the larger areas that it has been designed for have begun and these show that the homogeneity of the system is not yet as high as specified. The cause of this has been at least partially identified as due to a misalignment in the lamp optics and servicing these is expect to yield significant improvements to the large-area accuracy of the system.

In parallel to improving the homogeneity of the system, further technical additions are planned including:

- Installation of a system for the regulation of sample temperature during testing;
- Installation of a system for controlling the bias lighting intensity and spectrum.
- Facilities for measuring in the dark without the need for chopping.

Together, these additions to the system will be used to facilitate the development of accurate, quantitative measurement protocols, in compliance with the IEC standard for performing such measurements [1], at both cell and mini-module level for the full range of photovoltaic technologies, including multi-junctions.

References

[1] IEC Standard 60904-8. *Photovoltaic devices – Part 8: Measurement of spectral response of a photovoltaic (PV) device*. 1998.

[2] Sommeling, PM, Rieffe, HC, van Roosmale, JAM, Schönecker, A, Kroon, JM, Wienke, JA, Hinsch, A. *Spectral response and IV-characterisation of dye-sensitized nanocrystalline TiO_2 solar cells*. Solar Energy Materials & Solar Cells 2000; **62:** 399-410.