SCANNING IQE-MEASUREMENT FOR ACCURATE CURRENT DETERMINATION ON VERY LARGE AREA SOLAR CELLS

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ABSTRACT

We developed a setup to measure the quantum efficiency and integral reflectance for large area solar cells where the cell is scanned underneath a 2x2 cm² illuminated area defined by a mask. Measurements with 90 wavelengths between 300 and 1200 nm on 12.5 x 12.5 cm² solar cells are obtained in less than 15 minutes with very low noise due to the good signal-to-bias ratio. A self-consistent scaling procedure based on the analysis of the internal quantum efficiency is used to account for scaling errors due to the electrical measurement and stray light. This analysis also provides data which enable the calculation of the current loss in the emitter of the solar cell. A method is introduced to identify the bias light level at which the small signal quantum efficiency coincides with the integral large signal response eliminating the need to take the complete quantum efficiency for many bias levels.

I. INTRODUCTION

The short circuit current of solar cells is the most difficult solar cell parameter to measure accurately unless a very similar calibrated solar cell is available for comparison under a sun simulator. If many solar cells differing in reflectance, area and spectral sensitivity are to be measured it is costly to have similar cells for each concept calibrated at an authorized institute for comparison. Outdoor measurements under the real sun are a solution [1], but are reserved for countries with abundant sunshine.

In principle the short circuit current can be determined from the spectral response (SR) after convolution with the sun spectrum. This method involves the following difficulties:

1) The whole area must be measured if good homogeneity of the solar cell is not guaranteed.
2) The SR must be taken at various bias light intensities in order to translate the small signal response into large signal response [2,3,4].
3) Scaling errors which may be introduced through various effects need to be corrected (usually included in spectral mismatch calculations [5] or self calibration methods [6])

For large area cells 1) means an enormous effort to achieve laterally homogeneous monochromatic illumination of sufficiently high intensity. Grating monochromators are less suited to produce high intensity large area homogeneous illumination. Most large area SR-setups described in the literature therefore use band filters [7] which are prone to crack due to the high operating temperatures [8].

It is much easier to get high quality measurements on small cell areas (e.g. 2x2 cm²) where a grating monochromator with its good wavelength resolution can be used to provide narrow bandwidth, high intensity and reasonable homogeneity with a halogen light source of around 100 W. Bias intensities up to several suns can be applied with still good signal to noise ratio (SNR).

However, measuring large area cells of e.g. 200 cm² means to sacrifice accuracy since scaling up everything in order to keep the SNR would mean to use a 50 x brighter light source (5 kW) which is impractical and expensive (cooling, ozone cleaning etc.).

Our low-cost/high accuracy approach is to scan the large area solar cell underneath a 2x2 illuminated spot, therefore maintaining the SNR and moving the problem to longer measurement times. Our scanning setup measures a 12.5 x 12.5 cm² with 90 wavelengths in less than 15 minutes which is not much more than with full area setups so that this drawback is acceptable.

We will discuss our solution to problem 2) in the next section. A single bias light intensity will be identified at which the integral response equals the differential response. This bias intensity is determined by a bias-ramp at a single wavelength.

Problem 3) is solved by the analysis of the internal quantum efficiency (*IQE*) in a minimized way so that no further input is required. The necessary integral reflectance measurement must be taken over the entire area, particularly in case of multi-crystalline Si cells with their varying texture from grain to grain. An integrating sphere with 3 to 5% port area is usually used to measure the reflectance. Full area measurement without scanning would therefore require a very large sphere (about 50 cm diameter). Scanning the reflectance in the same apparatus using a reasonable size sphere (10-12 cm diameter) is again a low cost/ high accuracy alternative.

II. FROM DIFFERENTIAL TO ABSOLUTE SPECTRAL RESPONSE

Being a small signal measurement the spectral response and the quantum efficiency, respectively, are differential quantities [2-4].

$$SR^{diff}(\lambda) = \frac{dI_{SC}(\lambda)}{dI_{signal}(\lambda)} \quad (1)$$

I_{signal} denotes the incoming light intensity. In order to obtain the absolute value $SR(\lambda) = I_{SC}(\lambda)/I_{signal}(\lambda)$ at one sun the differential SR_{diff} must be known as function of the bias light intensity. The absolute SR can be determined via [4]

$$SR(\lambda, I_{SC\,bias}) = \frac{I_{SC\,bias}}{\int_0^{J_{SC}} \frac{dI_{signal}}{dI_{SC}} dI_{SC\,bias}} \quad (2)$$

Assuming that the reason for the non-linearity is a carrier density dependent effective diffusion length, which enters as differential quantity $L_{eff,diff}$ in the SR_{diff} and as absolute quantity L_{eff} in the absolute SR, then there must exist a bias intensity where $L_{eff} = L_{eff,diff}$. The shape of the absolute and differential spectral response curve should then be the same, i.e. one bias intensity to obtain $SR_{diff} = SR$ valid for all wavelengths.

To find this bias intensity it is best to choose a wavelength where the *IQE* is reduced to approx. 1/2 (around 1000 nm). The *SR* (or something proportional to *SR*, e.g. the measured signal) at this wavelength is taken in a bias-intensity sweep from $I_{SC,bias}$ = 0 up to the approximate short circuit current. The absolute *SR* is then determined using eqn.2. Follow the arrows in Fig. 1 to find the appropriate bias light starting at the bias intensity at which the absolute *SR* is desired.

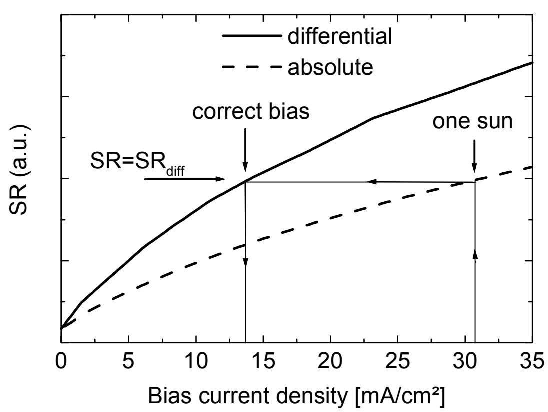

Fig.1: Procedure to find the correct bias level from a bias-light sweep at one wavelength.

III. SCALING PRINCIPLE

Wavelength independent scaling errors may be introduced by various effects such as incorrect 4-point contact setting, errors in the cell or mask area or difference in capacitance between calibration cell and measured cell due to a different size which affect the amplification (this is still a problem in our setup). These scaling errors have only a minor effect on the determination of diffusion lengths from the *IQE*, however, they are crucial for accurate current determination. We introduce a method to find this scaling factor with a procedure (similar to the one in [6]) as described in the following:

In the wavelength range where the fraction of light-generated carriers lost in the emitter is only a few percent (500-600 nm) and where the penetration depth of the signal light is less than 1/4 of the cell thickness (Ä 960 nm for a 300 µm thick cell) the measured internal quantum efficiency can be described by

$$IQE_{meas} = \frac{1}{k} \exp(-W_d / L_\alpha) \frac{1}{1 + L_\alpha / L_{eff}} \quad (3)$$

where k is a wavelength independent scaling factor. L_α is the light penetration depth and L_{eff} the effective diffusion length (in case of untextured surfaces).

The loss in the emitter can be approximated by a „dead layer“ with thickness W_d in which light-generated carriers have no chance of being collected [9]. For absorption lengths L_α much larger than W_d this is a reasonably good approximation.

One possible procedure to determine the parameters k, L_{eff} and W_d experimentally is the following:

1) Make a guess for L_{eff} and plot

$$\ln\left(IQE_{meas}\left(1 + L_\alpha / L_{eff}\right)\right) = -\ln(k) - W_d / L_\alpha$$

versus $1/L_\alpha$. A linear regression in the range of 500 to 700 nm will deliver the values k and W_d.

2) plot $$\frac{\exp(-W_d / L_\alpha)}{IQE_{meas}} = k\left(1 + \frac{L_\alpha}{L_{eff}}\right)$$

versus L_α. Linear regression in the range between ~700 nm and ~940 nm will give the values k and L_{eff}. This L_{eff} is the input for the second iteration. The method converges rapidly (2-4 iterations) even with a starting value of $L_{eff} = \infty$. No additional parameters need to be known so that the procedure is easily automated.

Fig. 2 shows a plot of the inverse *IQE* versus L_α before and after the „dead layer“ emitter correction. The simple dead layer model is justified as the corrected curve becomes a straight line.

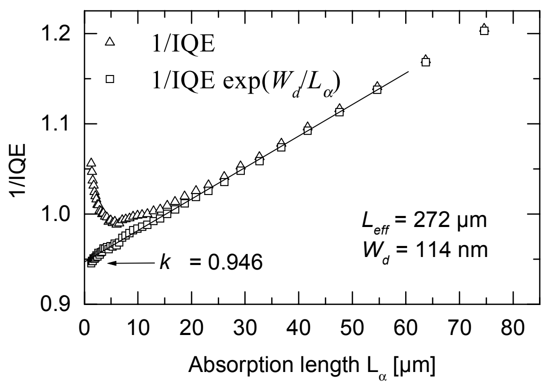

Fig. 2: 1/*IQE* vs. L_α plot with an without emitter correction.

After finding the scaling factor *k* the current density can be calculated by

$$J = k \int_{\lambda_{\min}}^{\lambda_{\max}} EQE_{meas}(\lambda)\phi(\lambda)d\lambda$$

where $f(l)$ denotes the photon flux of the desired spectrum. Note that this is the photo-generated current density according to the diode equivalent circuit and not the short circuit current which may be reduced by the shunt- and series resistance.

This correction method is only possible if a measurement of the integral reflectance is available. While for a full area *IQE* evaluation the reflectance must also be taken on the entire cell area, the scaling algorithm is sometimes preferably applied on a spot measurement of the *EQE* and reflectance since vast inhomogeneities in emitter quality and effective diffusion length may cause invalidity of the usual *IQE* description [10].

We found that it is important to take into account that not all light which is not reflected is absorbed [11]. In this wavelength range the partly absorbed light in the front metal grid must be taken into account. Therefore its reflectivity $R_{metal}(\lambda)$ must be known. We take the *R* and *IQE* only on the non-shadowed cell region (*M* = metallized fraction)

$$R = \frac{R_{meas} - M\,R_{metal}}{1 - M}\ ,\ IQE = \frac{EQE}{(1-M)(1-R)} \qquad (4)$$

IV. DESCRIPTION OF THE SETUP

The light of a 150 W tungsten-halogen lamp is chopped at 237 Hz and focussed into a grating monochromator. An optical filter cuts off the higher harmonics which superimpose the monochromatic light in the range between 670 nm and 1200 nm leaving the monochromator. A few percent of the light is then diverted onto a monitoring solar cell by reflection on a quartz glass plate.

The monitoring cell is used to correct drifts in the lamp intensity. The transmitted light is collimated by a lens and illuminates the solar cell homogeneously through a mask with 2x2 cm aperture size (the homogeneity is achieved by sacrificing the margins of the beam). Bias light from another 150W halogen lamp additionally illuminates the cell only through the mask so that the current density is kept within a few hundred mA. A remote-sense current/voltage converter keeps the cell at the programmed voltage, normally 0 V, and amplifies the signal current with 2 V/mA. A similar amplifier conditions the signal of the monitoring cell. Two EG&G 7220 Lock-In amplifiers evaluate the modulated signals.

The water-cooled sample stage, kept at 25°C, is mounted on an x-y table driven by stepping motors. Signal currents from the solar cell and the monitoring cell are recorded while the table moves continuously with 10-15 cm/s. For several amplifier-related reasons it proved to work best if the light spot never leaves the cell area, particularly if intense bias light is used.

About 200 lock-In readouts are recorded per wavelength on a 10x10 cm cell, where the lock-in amplifier already supplies some averaging (inherently via the 10 ms time constant). These readouts are weighted with the momentary table speed and averaged to provide a single value per wavelength.

Spatial resolution is not the intention of the setup since very fast LBIC systems with high resolution are much better suited for this purpose [12]. The long measurement time of several seconds per wavelength implicate very low noise data.

In case of reflectance measurements an integrating sphere replaces the mask. Up to 4 reflectance standards (*R* = 2...99%) are measured in advance as reference. The distance between the output port of the sphere and the samples is 0.5 to 1 mm.

V. EMITTER LOSS ANALYSIS

Another useful application of the dead layer approximation described above is to quantify the current loss in the emitter. The analysis described in section III yields the thickness of the dead layer W_d and the effective diffusion length L_{eff} without further input. The procedure to calculate the emitter loss with these values is as follows:

In the very short wavelength regime where the dead layer approximation is poor the *IQE*-loss is calculated from the experimental *IQE* after scaling and a (usually small) correction for the bulk loss :

$$IQE_{emi.loss,I} = 1 - k\,IQE_{meas.}\left(1 + L_\alpha / L_{eff}\right) \qquad (5)$$

For longer wavelengths where light reflection at the rear becomes important the simple description of the base *IQE* is inappropriate. However, the dead layer approximation becomes very good so that in this second regime the emitter loss may be described by

$$IQE_{emi.loss,II} = 1 - \exp\left(-W_d / L_a\right) \qquad (6)$$

The wavelength λ_1 that separates the two regions is determined by the condition that only a small fraction of the light is lost in the emitter, e.g. 3%. Fig. 3 illustrates the *IQE*-losses in the two regimes as shaded areas.

In order to obtain the current loss $J_{loss,emi}$ as a general characteristic of the emitter the emitter-*IQE* loss in these two regimes has to be convoluted with the photon flux ϕ of the desired spectrum.

$$J_{loss,emi.} = \int_{\lambda_{min}}^{\lambda_1} IQE_{emi.loss\,I}\,\phi\,d\lambda + \int_{\lambda_1}^{\lambda_{max}} IQE_{emi.loss\,II}\,\phi\,d\lambda \tag{7}$$

If the loss of a particular cell is to be determined the reflected light must be subtracted.

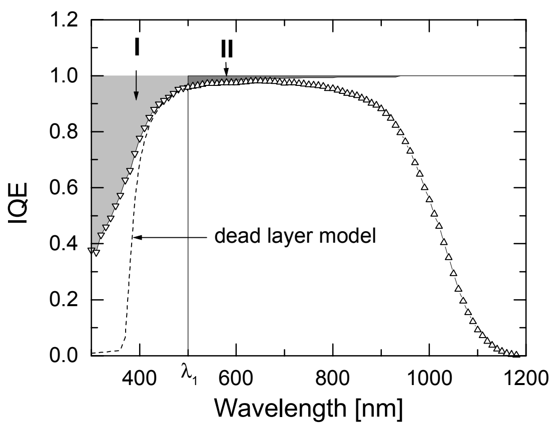

Fig. 3: Calculation of the current loss in the emitter by considering two regimes: (I) The difference between *IQE* = 1 and the experimental curve corrected by the bulk loss contribution shown as ò and (II) using the dead layer model (dotted). ∆ denotes the experimental curve.

VI. SUMMARY

The scanning SR/Reflectance method allows high accuracy quantum efficiency measurements and short circuit current determination at relatively low cost for large area inhomogeneous solar cells. The availability of a full area reflectance measurement enables the meaningful detailed evaluation of the internal quantum efficiency.

Finding the bias light intensity at which the small signal response coincides with the absolute response by a bias-sweep measurement at one wavelength allows to measure the (quasi-) absolute *SR*-spectrum in a single wavelength scan. A minimized *IQE*-analysis provides a scaling factor correction important for the calculation of J_{SC}, the effective diffusion length and a single parameter describing the emitter quality. This analysis also enables the quantification of the current loss in the emitter.

We plan to apply the presented scaling algorithm to LBIC measurements in the near future in order to improve the accuracy in L_{eff} -maps and to generate mappings of the "dead layer“ thickness as emitter quality criterion.

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