IMPROVING QUANTUM EFFICIENCY MEASUREMENT IN LARGE AREA SOLAR CELLS BY USING APPROPRIATE BIAS ILLUMINATION

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ABSTRACT: This paper presents an improvement for the measurement of the external quantum efficiency (EQE) of large area crystalline silicon solar cells. The main concept is to replace the standard white light source for the bias illumination by infrared light emitting diodes (LED). We show that, even for strongly injection dependent lifetime or back surface recombination velocity, similar carrier injection can be achieved in the bulk and at the backside of the wafer, but with a DC bias short circuit current lower by a factor three with the LED. However, the consequence of the different spectra is a discrepancy of the injection level close to the front surface, which can modify the recombination in the front part of the wafer and the EQE, compared to white light illumination. Simulations with PC1D for different cell models as well as experimental results on multi crystalline solar cells demonstrate that the absolute error of this method is below 1% and thus smaller than the typical discrepancies observed between leading calibration labs [1]. The LED bias illumination causes an improvement of the signal-to-noise ratio by a factor three and better and thus allows faster and more precise measurements, and puts less stringent requirements on the electronics.
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1 INTRODUCTION

The Quantum Efficiency (QE) measurement is one of the most significant characterisation tools for solar cells. It faces however a major problem for large area cells: the correct measurement method (DSR = differential spectral response [2]) requires the application of a DC bias light with intensity ranging between 0 and 1000Wcm^{-2} with a white light spectrum similar to AM1.5g in addition to a low intensity, modulated quasi monochromatic light [2].

The common systems use a white bias light, which adjust an injection level up to those obtained in standard testing conditions (STC). This is essential, because of the injection dependence of carrier lifetimes and surface recombination velocities. The bias light can though creates a DC current up to 15A for a 20 x 20 cm^2 cell under STC, which is important compared to the small signal given by the monochromatic light (a few µ to mA). Besides, accurate measurements require to maintain the cell in short circuit conditions under modulated illumination. Presently there is no transimpedance amplifier (TIA) available for such amperage.

To improve the signal-to-noise ratio caused by a high bias current, the idea is to avoid the lower wavelengths of the spectrum by using narrow band LEDs with central wavelength of 950 nm. The generation barycentre under this illumination dislocates to deeper regions of the cell and thus generate a smaller short circuit current, but with injection condition similar to those of white light in most of the wafer. Wavelengths below 800 nm have penetration lengths below 10 µm and hence generate electron-hole pairs close to the pn-junction. The effect for the bulk injection level of these wavelengths is thus expected to be marginal.

However, the topmost layers of the cell will cause an error compared to measurements under STC caused by the misfit of the injection profile. The simulated and measured extent of this error is presented in this paper.

2 MEASUREMENT SYSTEM

The system applied by Q-Cells AG uses a Xe – arc lamp whose light is optically chopped and spectral analysed by a series of narrow band inference filters. A schematic configuration is shown in Fig. 1.

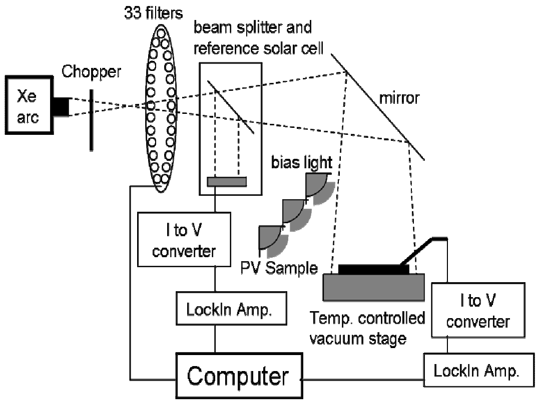

Figure 1: Q-Cells filter DSR system with a 320-1200 nm wavelength range.

The calibration of the system demands a measurement of a primary cell. Several halogen spotlights or LED arrays can be implemented as bias illumination. The irradiance of the bias light is adjusted by measuring the short circuit current of the primary cell. The inhomogeneity of the bias light is approximately 10% over the area of 20 x 20 cm^2. The spectral characteristics of the used bias lights compared to the recommended standard illumination AM1.5g are shown in figure 2.

The I to V converter is ideally performed by a transimpedance amplifier (TIA). As available TIA's are limited to ranges of 5 A, cells with higher I_{sc} are measured by a parallel resistance and a reverse DC voltage. This method creates a systematic error proportional to the parallel resistance of the cell.

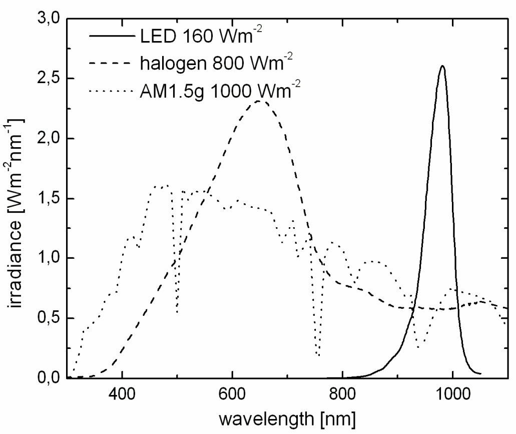

Figure 2: Spectra of the used halogen and the LED bias light compared to AM1.5g

3 SIMULATION WITH PC1D

3.1 Alignment of irradiance

To adjust the ideal irradiance of the LED illumination, the injection profile over the depth is aligned to the profile under STC with respect to an optimal match in volume regions of the cell. Figure 3 shows the resulting profiles for a model with typical parameters for an industrial cell with p-type basis with a resistivity of 1.8Ωcm, heavily n-doped emitter and Al back contact.

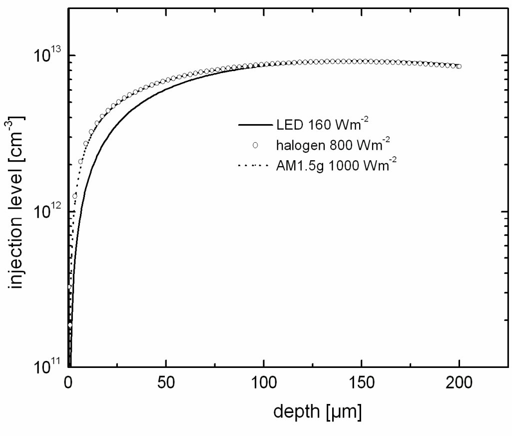

Figure 3: Simulated profiles of the injection level of the halogen and the LED bias light compared to AM1.5g conditions.

Table I: Results for the optimal agreement of injection profiles in volume region

bias light	irradiance $[Wm^{-2}]$	bias current density $[mAcm^{-2}]$
AM1.5g	1000	32.4
halogen	800	34.3
LED	160	8.7

The irradiance and the resulting bias current for the best agreement of the injection profiles are shown in Table I. The bias current under LED illumination is more than factor three times smaller compared to the white lights. The improvement for the signal-to-noise ratio is thus factor three and better.

The acquired irradiance of the LED bias light generates similar injection profiles as AM1.5g also for lower intensities of illumination and other lifetimes. Figure 4 shows the injection level in depth of the half wafer thickness over the light intensity were 1 equals 1000 Wm^{-2} for AM1.5g and 160 Wm^{-2} for the LED illumination. The different Fe_i concentrations represent a strong injection dependent lifetime at different levels. In all cases the LED illumination is in good agreement with AM1.5g.

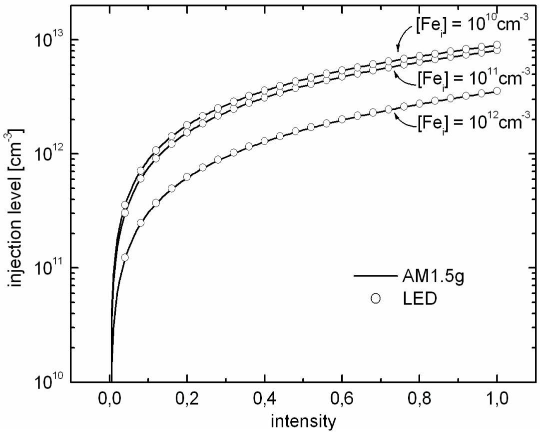

Figure 4: Injection level at depth of half wafer thickness over the bias intensity of AM1.5g and LED illumination. Different concentration of Fe_i impurities represent strong injection dependent lifetimes at 178, 17.8 and 1.78µs.

3.2 Results for EQE

Several parameters of the cell model were varied and the influences on the deviance ΔEQE due to the different bias illuminations were investigated. ΔEQE is defined as the difference between the EQE under AM1.5g and the EQE under other bias illuminations. The mean focus is on the injection dependent carrier lifetime τ_{bulk} and the recombination velocities of the rear (S_{back}) and front surface (S_{front}). The most decided effect is found at highly injection dependent lifetimes due to defects with a symmetry factor of the carrier capture cross sections $k=\sigma_n/\sigma_p>>1$ like the Fe_i defect with $k\approx700$ [3],[4]. Such defects highly affect the lifetime of the p-doped basis material. We consider interstitial iron as a prototype defects that creates strong injection dependent of the lifetime [5], even though in the initial state of the cell iron is likely to be in the form of less electrically active Fe-B pairs in p-doped substrates. The basis doping of 1.8Ωcm ensures a strong injection dependence between injection levels of 10^{12} and 10^{13} cm^{-3}[6].

Defects with a $k << 1$ do not affect the injection dependence of the p-doped basis. They do not affect the n-type material either, as the lifetime in the emitter is limited by auger- instead of SRH - recombination, due to high doping densities.

The simulation of injection dependent surface recombination velocities with PC1D includes a single defect level and is thus treated like the recombination in the volume. A serial of simulations showed, that the injection dependence of S_{front} is negligible for ΔEQE. The S_{back} injection dependence shows comparable effects such as the lifetime of the basis material. This means no effect on ΔEQE by k<<1 and high effect by k>>1.

Some of the injection independent parameters can influence the profile of the injection level and thus affect the injection dependent values which influence ΔEQE. ΔEQE moderately increases with wafer thickness. The optical film thickness of an anti-reflex coating and the doping density of the emitter have small influence on ΔEQE.

The results for a model with different densities of Fe_i impurities and an injection dependent back surface recombination velocity are shown in Fig. 5. The noise in this plot is caused by the roundoff error of PC1D due to the small signal of the monochromatic light extracted from high bias current density.

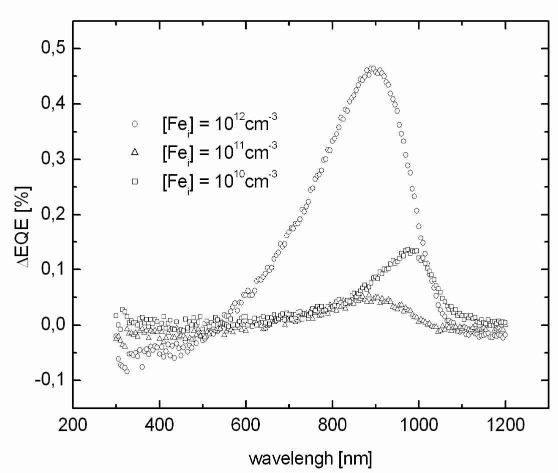

Figure 5: ΔEQE for an industrial cell model with τ_{bulk} dominated by the Fe_i defect of different concentration. Internal optical reflections are neglected due to conflicts of PC1D.

3.3 Numerical problems of PC1D

PC1D affords a bias light adjusted IQE simulation, which unfortunately produces incorrect results, shown in figure 6.

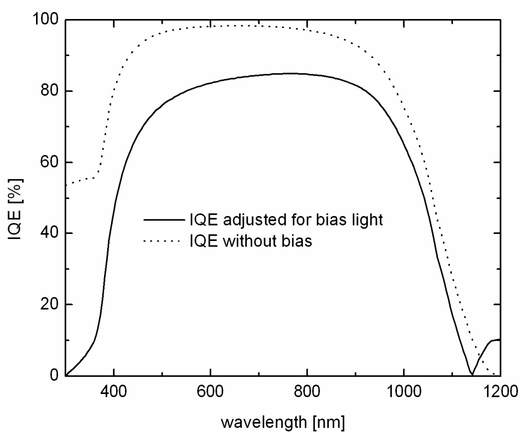

Figure 6: Erroneous simulation of the IQE adjusted for bias light compared to the same cell without bias illumination

An alternative access to the EQE is the simulation of short circuit currents under monochromatic light and a secondary light source as bias light. The EQE then is

$$EQE = \frac{hc}{q\lambda} \cdot \frac{j_{M+B}(\lambda) - j_B}{E_M(\lambda)}, \qquad (1)$$

where λ is the wavelength, $j_{M+B}(\lambda)$ is the short circuit current density under the illumination of the monochromatic and the bias light, j_B is the short circuit current density under illumination of the discrete bias light, and $E_M(\lambda)$ is the spectral irradiance of the monochromatic illumination.

Another problem of PC1D occurs if internal reflections are used combined with a secondary light source. With it the simulated EQE using equation (1) attains negative values. As a consequence the internal reflectivity is set to zero and neglected for simulations of the EQE.

4 EXPERIMENTAL RESULTS

4.1 Measurements with TIA and small cells

With a 25 cm^2 multi crystalline Silicon solar cell the differential EQE was measured with a TIA under different bias illuminations and intensities. The absolute EQE is acquired by [7]:

$$EQE_{abs}(\lambda)\big|_i = \frac{1}{i}\int_0^i EQE_{diff} \cdot di^*, \qquad (2)$$

where i is the intensity factor of the irradiance. The results for the absolute EQE under 800 Wm^{-2} halogen, 160 Wm^{-2} LED and no bias illumination are shown in figure7.

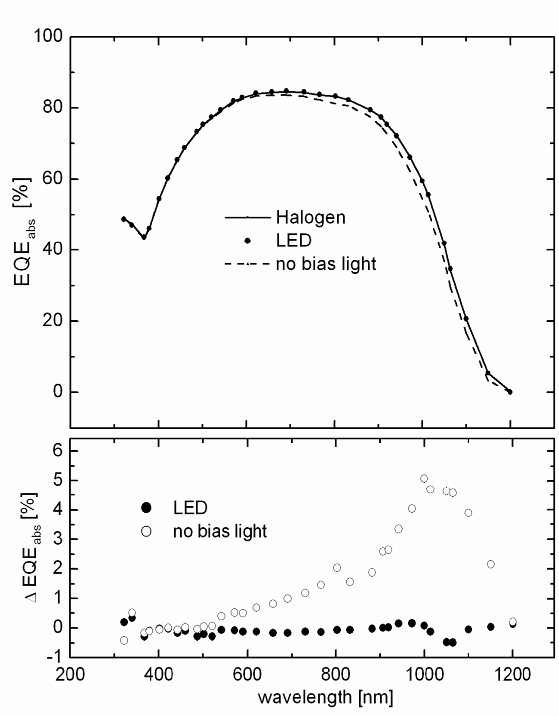

Figure 7: Top: Absolute EQE under Halogen, LED and no bias illumination. Below: Difference of EQE under LED and no bias light to the EQE under Halogen illumination.

A common technique to calibrate the STC - I_{sc} of a PV device is to convolve the absolute EQE with the STC-spectrum AM1.5g [7]:

$$I_{sc} = A\int_{\lambda_1}^{\lambda_2} EQE_{abs}(\lambda) \cdot \frac{q}{hc} \cdot \lambda \cdot E_{AM1.5g}(\lambda) d\lambda \,, \quad (3)$$

where A is the area of the sample, q is the elementary charge, h is the Planck's constant, c is the vacuum speed of light and $E_{AM1.5g}$ is the spectral irradiance of AM1.5g in $Wm^{-2}nm^{-1}$. Using this method for the investigated cell, the mismatch between the I_{sc} resulting from halogen bias light measurements compared to LED bias light is 0.18% and thus negligible compared to the discrepancies between leading calibration labs [1].

4.2 Measurement of large area cells

The I to V converter for large area cells is performed by a parallel resistance and a reverse DC voltage. The differential EQE is measured under halogen illumination of approximately half a sun and under equivalent LED irradiance. As mono crystalline cells have usually less injection dependent material properties compared to multi crystalline they are less sensitive to different bias illumination. The experiments are thus focused on the multi crystalline material.

The results to the differences between halogen and LED measurements for several crystalline Silicon solar cells are shown in figure 8. For all examined cells the mismatch is below 1%, excluding the first two measuring points where deviation is caused by too much noise of the halogen measurement. Indeed the result in UV and blue are more accurate with the LED set up.

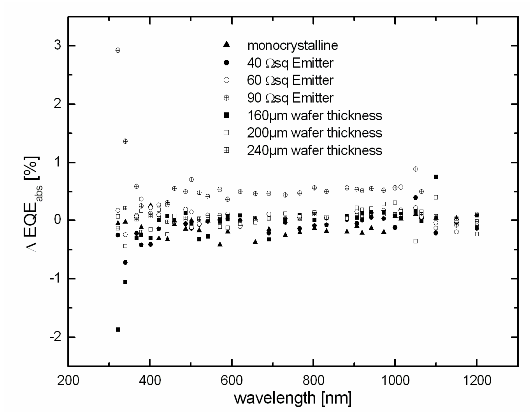

Figure 8: ΔEQE for one mono crystalline and several multi crystalline Silicon solar cells. Different thicknesses and emitter doping densities were tested.

5 CONCLUSIONS

The introduced method of an infrared LED bias illumination for DSR measurements demonstrates a good agreement to the common halogen bias light measurements. The mismatch between these methods for all investigated cells is below 1% in the EQE, excluding the points of high noise in near UV. For calibration of the I_{sc} via the absolute EQE the discrepancies between halogen and LED measurement of a tested injection dependent cell is 0.18% and is thus feasible for calibration procedures.

The DC bias current under LED illumination could be reduced by 70% compared to halogen bias. This allows a more precise and faster measurement. Another advantage of this technique is the applicability of available TIA for the measurement of large area cells which would otherwise exceed the ranges of these systems.

The LED bias light appears to be applicable for DSR measuring and might be as well for other bias applications such as local beam induced current (LBIC).

6 REFERENCE

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