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ScienceDirect

Energy Procedia 77 (2015) 113 – 118

Energy Procedia

5th International Conference on Silicon Photovoltaics, SiliconPV 2015

Rapid testing of external quantum efficiency using LED solar simulators

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Abstract

A new generation of solar simulators is based on light emitting diode illumination sources. These measurement systems offer the opportunity to adjust the light spectrum as close as possible to the AM1.5G reference spectrum. Additionally, they provide the technical basis to combine power measurements with a spectral resolved analysis. Such an application is the determination of the quantum efficiency, which results in valuable additional cell information such as front and rear surface recombination, diffusion length, or emitter dead layer thickness. In this work, a fast method to determine the external quantum efficiency (EQE) of a solar cell using a LED solar simulator is presented. The measurement time of our LED-EQE approach could be reduced to less than half a second as no mechanical parts such as monochromators are involved. Due to the finite spectral band-width of the LEDs an adapted data analysis approach has been developed, which leads to results that show excellent agreement with standard EQE measurements.

Peer review by the scientific conference committee of SiliconPV 2015 under responsibility of PSE AG

Keywords: LED solar simulator; quantum efficiency; loss analysis

1. Introduction and motivation

The development of a new type of solar simulators based on light emitting diode (LED) illumination has been very intense during the last few years. [1-4] The increased accuracy of power measurements due to a spectrum that coincides to a high degree with the AM1.5G reference spectrum has been a first major application. Beyond this type

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Peer review by the scientific conference committee of SiliconPV 2015 under responsibility of PSE AG
doi:10.1016/j.egypro.2015.07.018

of measurements under standard test conditions, LED solar simulators open a path towards rapid spectral testing of solar cells and modules. One application is the determination of the external quantum efficiency (EQE). Based on this spectral information a detailed loss analysis of solar cells can be implemented and cell parameters such as diffusion length or surface recombination losses can be extracted. Another important field of applications concerns the spectral resolved loss analysis of PV modules and its components. [5]

A lock-in or Fourier transform technique can be used to determine the EQE. [6] In this work, great emphasis was placed on a method which is applicable to any LED-based solar simulator. A mathematically strict data analysis for broad-band LED illumination has been developed to resolve the challenges that appear when the illumination source is not exactly monochromatic. Typically, such an LED-based EQE test is characterized by finite spectral band-widths of the individual LEDs of up to 100nm. The basic setup allows reducing the measurement time to less than half a second. To verify the analysis method, it is applied to experimental results obtained with an LED solar simulator and compared to a conventional EQE measurement using a double-monochromator. Furthermore, it will be shown how the obtained results can be used to perform a detailed solar cell loss analysis.

Due to the reduced measurement time it is feasible to develop a rapid spectral test which is suitable for in-line applications. Furthermore, there are two major advantages compared to the conventional approach where a solar simulator and an additional EQE measurement setup are employed. First, an LED solar simulator can provide a full-area illumination of cells making a scanning of samples obsolete. In particular, an EQE measurement on entire modules appears to be possible as an LED light source can be scaled up to module size. Second, power and spectral response measurements can be combined in a single tool saving valuable processing time and investment cost. In this way, the spectral mismatch correction can be implemented into the solar simulator itself.

2. Experimental approach and data analysis

As in conventional EQE-tests the determination of the quantum efficiency values is based on the dependence of the short circuit current density i_{SC} on the external quantum efficiency $EQE(\lambda)$ and the irradiation $I(\lambda)$ as functions of the wavelength λ

$$|i_{SC}| = \mathrm{q/hc} \int d\lambda\, I(\lambda) \cdot \lambda \cdot EQE(\lambda). \tag{1}$$

However, the major difference between a standard EQE-measurement using monochromators and the proposed LED-EQE method is that the solar cell is not illuminated with a monochromatic light beam but with a rather broad spectrum of various LED channels. There are no mechanical parts in this setup such as filter wheels or rotating gratings which would increase the measurement time.

The reference EQE data are determined with the solar cell analysis system LOANA by pv-tools GmbH, which include an EQE measurement setup that provides monochromatic light between 280-1600 nm. The typically used bandwidth of the irradiated spectrum is 8 nm FWHM. The measurement time is 1 second per wavelength and 2x2 cm² spot, thus it takes over half an hour to determine the quantum efficiency of an entire 15.6x15.6 cm² sample.

The LED-EQE method is tested with the LED-solar simulator SINUS 220 by WAVELABS featuring 21 different LED channels. The intensity of each channel is individually adjustable and shows spatial homogeneity over the entire 15.6x15.6 cm² cell area. A spectrometer and a reference cell are integrated in the LED unit. Thus, the spectrum $I(\lambda)$ is automatically detected at each illumination step. The integrated LEDs cover a spectral range between approximately 350 nm and 1050 nm. The spectral characteristics $I_{k=1..21}(\lambda)$ of the LED channels show a spectral bandwidth of $\Delta\lambda_k$ ~ 15-110 nm FWHM, see Fig. 1. Thus, the illumination with a single LED channel yields the average value of the weighted EQE values in the LEDs wavelength range, where the weighting factor is the spectrum of the LEDs. This average quantum efficiency value $EQE(\lambda_k)$ is assigned to an effective wavelength λ_k for each individual LED channel by rewriting Eq. (1) as

$$|i_{SC}| = q/hc \cdot \langle\lambda\rangle \cdot EQE(\langle\lambda^2\rangle/\langle\lambda\rangle) \tag{2}$$

Thus we find that these pairs $\{\lambda_k, EQE\ (\lambda_k)\}$ are obtained by considering the mathematical moments $\langle\lambda^n\rangle$ of each individual LED spectrum $I_k(\lambda)$ defined as