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A simple method for quantifying spectral impacts on multi-junction solar cells

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Abstract

A method to quantify spectral effects on the electric parameters of multi-junction solar cells is presented. The method is based on measuring the short circuit current of at least two monitor cells. Ideally these monitor cells have the same spectral responses as the subcells in the investigated multi-junction solar cell. In contrast to the subcells, the current of the individual monitor cells can be measured separately. This allows conclusions to be drawn about the spectral impact on the current mismatch of the multi-junction solar cell. A spectrometric evaluation method is then applied.

The method has been tested experimentally with three concentrator modules using III–V triple-junction solar cells. These modules were measured outdoors for several months under variable solar spectral conditions. In parallel, the IV curves of the modules and the current of two component cells were measured. A spectral parameter Z was derived from the monitor cell current signals, which was correlated to the short circuit current and the fill factor of the modules. A linear correlation was found between Z and the normalized short circuit current of the concentrator modules. Translation equations were derived from the linear correlation. These enable the calculation of a module's short circuit current under any spectral conditions. In particular, the short circuit currents of the modules were derived for direct normal irradiance of 850 W/m^2 and spectral conditions corresponding to the AM1.5d low AOD spectrum. This is an important step towards comparing the performance of modules which show strong spectral sensitivity. Future rating methods can benefit from the presented simple method for quantifying spectral impacts on multi-junction solar cells. Furthermore, the method can be of interest for tuning the spectrum of pulsed solar simulators.

Keywords: Spectrum; Monitoring; Spectrometric; Rating; PV; Module

1. Introduction

Multi-junction solar cells consist of several subcells with different bandgaps which utilize different parts of the solar spectrum. Consequently, thermalization and transmission losses are reduced and a multi-junction solar cell can convert the solar spectrum more efficiently than a single-junction solar cell. Today, the highest efficiencies are achieved by monolithic III–V triple-junction solar cells (Geisz et al., 2008; Guter et al., 2009; King et al., 2007). The subcells of monolithic multi-junction solar cells are electrically connected in series. Therefore, the short circuit current I_{SC} is determined by the subcell which generates the lowest current. This current limitation is the reason for the pronounced spectral sensitivity of monolithic multi-junction solar cells (Faine et al., 1991; Hein et al., 2001; Kurtz et al., 1990).

Terrestrial applications of III–V multi-junction solar cells are typically in concentrating photovoltaic (CPV) systems (Luque and Andreev, 2007). The characterization of CPV modules equipped with multi-junction solar cell is still challenging. So far, the modules have been measured

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outdoors due to the fact that a quasi-parallel light source on large area is required for indoor measurements. On the other hand, outdoor measurement implies ever changing environmental and spectral conditions. In particular the latter have been not considered so far. Thus, a direct comparison of measurement performed on different modules is difficult. As a result of the combined impact of light concentration and the application multi-junction solar cells, the characterization of CPV modules is still challenging. In this context, one should note that new solar simulators for concentrator modules are currently under development (Anton et al., 2005; Dominguez et al., 2007; Rumyantsev et al., 2006), but these simulators do not allow spectral influences to be investigated. Today a CPV module must be measured outdoors under different solar spectra in order to obtain information about the spectral impact on module performance. Therefore, the solar spectrum must be monitored in parallel to recording the IV curve of the module. In earlier work, the solar spectrum was monitored by using spectroradiometers (Létay et al., 2004; McMahon et al., 2008; Tsutsui and Kurokawa, 2008). A spectroradiometer delivers the complete spectral information, enabling a detailed study of the solar spectrum. Once the spectral distribution is measured the average photon energy can be calculated which is becoming a popular method for quantifying spectral impacts (Krishnan et al., 2009; Minemoto et al., 2009, 2007; van Sark, 2008). One disadvantage of spectroradiometers is that their application is not trivial, especially when outdoor solar spectra are to be measured continuously and reliable over several months. In this paper, an alternative method to monitor the solar spectrum and to quantify its impact on multi-junction solar cells is presented. The measurement technique is based on measuring the current of at least two filtered monitor cells. This makes the method more robust than the application of spectroradiometers. A spectrometric method (Adelhelm and Bücher, 1998; Meusel et al., 2002) is then applied to quantify the spectral impact. This method enables conclusions about the characteristics of the monitored spectrum to be drawn from the measured monitor cell currents. This information can be used to derive the concentrator module performance under given spectral conditions.

2. The spectrometric method

The presented spectrometric method can be applied to investigate spectral influences on the electric properties of multi-junction solar cells. In principle, there are two prerequisites for successful application of the method:

(1) A set of monitor cells with different spectral responses is required. Ideally, the absolute spectral response $SR_i(\lambda)$ of monitor cell i (where λ is the wavelength) is equal to the spectral response of the corresponding subcell in the multi-junction cell. It is recommended to use component cells (also known as “isotype” cells) as monitor cells. The structural composition of component cells is similar to multi-junction cells. In contrast to the multi-junction solar cell, however, the component cell has only one electrically active subcell. Since the other subcells do not have a pn-junction, they are electrically inactive. However, these electrically inactive subcell materials absorb/filter light. Consequently the spectral response of a component cell is expected to be equal to the spectral response of the corresponding subcell in a multi-junction solar cell. An alternative to the use of component cells is the use of single-junction solar cells combined with appropriate bandpass filters.

(2) A defined reference spectrum $E^{ref}(\lambda)$ is required. Whereas flat-plate photovoltaic modules are evaluated using the AM1.5 g spectrum as the standard reference (IEC, 1989), the AM1.5d low AOD (Gueymard et al., 2002) spectrum is often used as the standard for concentrator modules.

The short circuit current density J_{SC} of a solar cell is a function of its spectral response and the irradiance spectrum. With an irradiance spectrum of $E^{ref}(\lambda)$, the short circuit current density J_i^{ref} of monitor cell i is calculated to be:

$$J_i^{ref} = \int SR_i(\lambda) \cdot E^{ref}(\lambda) \cdot d\lambda \tag{1}$$

In a calibration procedure, J_i^{ref} is determined for each monitor cell i. In particular the measurement of the spectral response and a current mismatch correction must be included in the calibration procedure; as described in the IEC standard 60904 Part 7 and 8.

The short circuit current densities of the calibrated monitor cells are measured to monitor the spectra of interest. Each monitor cell i generates a certain short circuit current density J_i^{mon} for the monitored spectrum $E^{mon}(\lambda)$:

$$J_i^{mon} = \int SR_i(\lambda) \cdot E^{mon}(\lambda) \cdot d\lambda \tag{2}$$

The ratio of J_i^{mon} to J_i^{ref} is R_i and describes the current generated under the monitored spectral conditions relative to the current generated with the reference spectrum:

$$R_i = \frac{J_i^{mon}}{J_i^{ref}} = \frac{\int SR_i(\lambda) \cdot E^{mon}(\lambda) \cdot d\lambda}{\int SR_i(\lambda) \cdot E^{ref}(\lambda) \cdot d\lambda} \tag{3}$$

Since the different monitor cells are sensitive to different spectral bands, a conclusion about the spectral distribution of $E^{mon}(\lambda)$ can be drawn by analyzing the current ratios R_i. A spectrometric method (Adelhelm and Bücher, 1998; Meusel et al., 2002) is applied for the analysis. In the following section, this method is described using two monitor cells as an example, and later a more general description is given for an arbitrary number of monitor cells.

2.1. Using two monitor cells

The usage of two monitor cells is recommended to investigate spectral impacts on dual-junction cells. However, it is