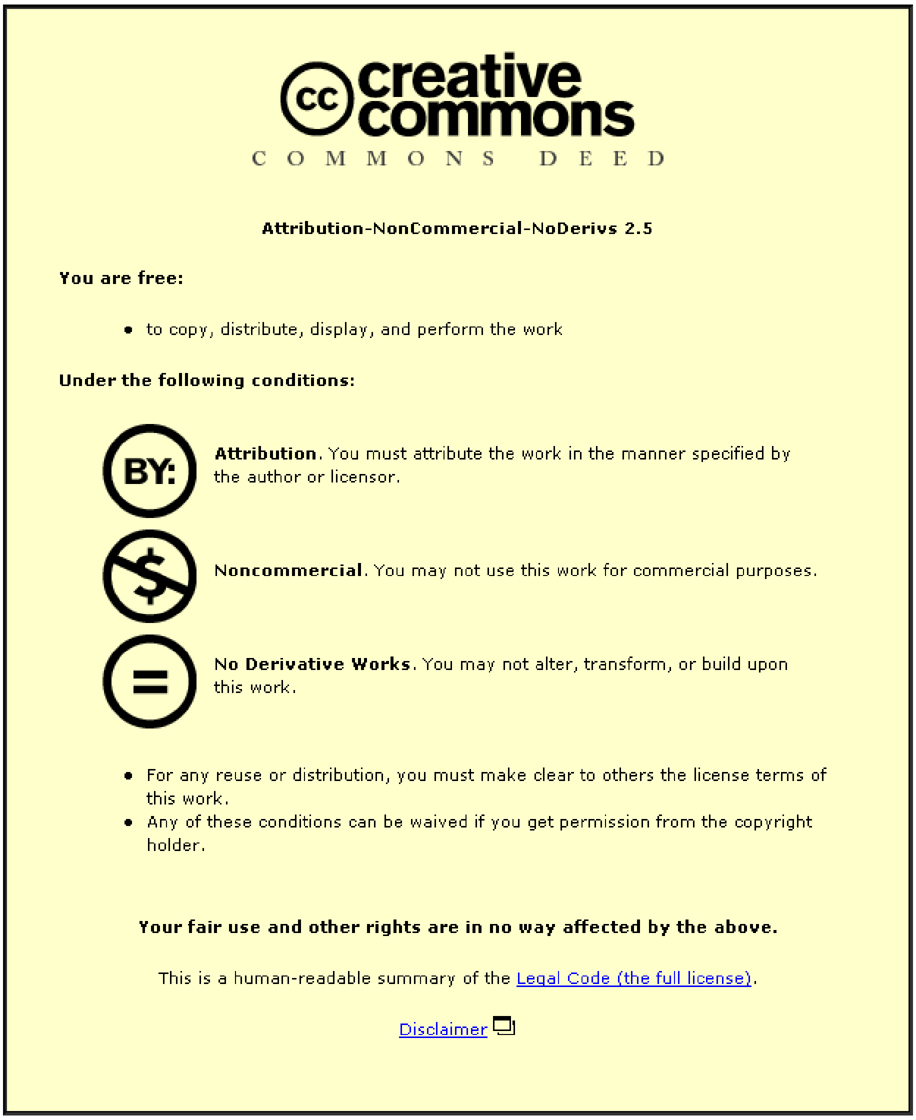

Towards an Accurate and Automated Characterisation of Multi-Junction Solar Cells

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Abstract

A theoretical approach of automated characterisation of single as well as multi-junction solar cells has been developed. The method will be implemented in CREST's measurement system. It delivers not only I-V characteristics at reference spectrum but also absolute spectral response of the test cell. Thus it opens the way for inline spectral response measurements. The method requires nothing more than a multisource solar simulator, some basic information about the test cell and a calibrated reference cell.

Single- and multi-junction measurement procedures are briefly reviewed; the automatic measurement approach is explained and underlined with real and simulation results.

1 Introduction

Multi-junction solar cells have led to record efficiencies in solar energy conversion but are extremely difficult to calibrate, especially in production relevant speeds. The high efficiencies have been achieved by stacking multiple solar cells, each responding to different spectral ranges of the incident spectrum. The increased device complexity has introduced new characterisation challenges as it still remains a major challenge to accurately measure multi-junction solar cells.

To do so, one needs to operate a multi-source or spectrally adjustable solar simulator (i.e. with filters). In this way, the spectral distribution of the simulator can be changed and stacked cells can be current matched or balanced to a reference spectrum. Furthermore, spectrometric characterisation can be carried out, which is a systematic investigation of the effects of current limitation on the device fill-factor, power output and efficiency.

All measurement methods available today require knowledge of the spectral response of each junction or at least use closely matched reference cells. This is costly and in the case of thin film silicon devices increasing uncertainty makes it virtually impossible to use "same" response reference cells as first the material is meta-stable and will change its spectral match during normal operation and second there will be a variation in the junction matching of modules during production. In order to eliminate this additional uncertainty, one needs to measure the spectral response of each junction of each module, which is time consuming and currently not possible in factory relevant time cycles, and normally not done on full size modules. Thus there is a clear need for a fast and automated method of cell calibration without the need of spectral response data of each cell junction beforehand.

The situation for single junction devices is not too different, especially when it comes to measuring the spectral response of large devices or if no closely matched reference cell is available as e.g. in the case of meta-stable devices such as amorphous silicon modules. Thus, a method applicable for all multi- and single-junction devices would be ideal.

In the following, an approach for automatic characterisation of multi-junction solar cells is presented that will not only reduce measurement time and costs, but also the uncertainty in the calibration process.

2 Comparison of device calibration methods and requirements

Before one is able to discuss an automated measurement process for single-junction (SJ) and multi-junction (MJ) solar cells, it is important to briefly review the today's characterisation methodologies and requirements.

2.1 Single-Junction

Typically SJ solar cells are measured with a reference cell with the spectral response closely matched to the test specimen. In this case, the theoretical short circuit current (I_{SC}) of the reference cell under the reference spectrum is calculated or the calibrated value CN at reference spectrum is used. The intensity of the solar simulator is then adjusted until I_{SC} is equal to CN and then the I-V curve of the test cell can then be acquired.

If the spectral response of the test cell is different to that of the reference cell, the additional uncertainty can be largely reduced by calculating the spectral mismatch M according

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to IEC60904-7. The CN of the reference cell under the reference spectrum can then be divided by the factor M and a new I_{SC} is achieved to which the simulator light intensity can be adjusted.

If the simulator light cannot be tweaked to the desired intensity, irradiance correction according to IEC60891 is required. This can be done if the test specimen is linear over the range of interest (IEC60904-10). To acquire the series resistance for voltage corrections, 2 or 3 measurements at different intensities are required.

If no reference cell is available, but the absolute spectral response of the cell is known, it is also possible to adjust the simulator light intensity to the calculated I_{SC} of the test cell at reference spectrum.

2.2 Multi-Junction

In this paper the focus is mainly given to two-terminal MJ solar cells, as others are easier to measure due to separate access to each junction.

Three different main methods have been developed. The difference between them lies in the initial requirements (i.e. absolute or relative spectral response of each sub-cell). Some are subdivided and further differ in the procedure of setting the simulator spectrum for matching the junction currents to that of a reference spectrum. A comparison of the methodologies can be found in a paper from the Fraunhofer Institute for Solar Energy Systems (ISE) [1].

However, ISE has further developed a reference cell method, described in detail in [2], which is fast, accurate and the most relevant for this paper, as the method of setting the simulator intensity and spectrum can be applied automatically in CREST's LED solar simulator. The principle requirement for this method is a multi-source solar simulator which allows intensity adjustments of each lamp without changing its spectral distribution.

In the case of a dual junction solar cell and two available adjustable light sources, each mainly influencing one junction, the simulator light can be adjusted by first solving the two dimensional linear equation system 1. The two unknowns A_1 and A_2 are representing the intensity factors of the light sources. The relative spectral outputs of the two light sources are e_1 and e_2 and the relative spectral response of the top- and bottom-cell are s_{TOP} and s_{BOT}.

$$\begin{aligned} A_1\int s_{Top}e_1 d\lambda + A_2\int s_{Top}e_2 d\lambda &= \int s_{Top}E_{REF} d\lambda \\ A_1\int s_{Bot}e_1 d\lambda + A_2\int s_{Bot}e_2 d\lambda &= \int s_{Bot}E_{REF} d\lambda \end{aligned} \tag{1}$$

With knowledge of the intensity factors, it is now possible to calculate the short-circuit density (J_{SC}) of the reference cell from each light source J_{RC}^{E1} (2) and J_{RC}^{E2} (3), where S_{RC} is the absolute spectral response. In the presented case of one reference cell, it is essential that this reference cell is responding over the complete range of all subcells.

$$J_{RC}^{E_1} = A_1\int S_{RC}e_1 d\lambda \tag{2}$$

$$J_{RC}^{E_2} = A_2\int S_{RC}e_2 d\lambda \tag{3}$$

The simulator light sources need to be adjusted separately until the correct I_{SC} of the reference cell is measured. Afterwards the I-V characteristic can be acquired as it would for a normal SJ solar cell. If the required light source intensities cannot be achieved, irradiance correction is possible when the same junction current balance is set and the device is linear in the range of correction.

With the method developed at ISE it is also possible to carry out a spectrometric characterisation. Detailed information about this can be found in [2].

2.3 Spectral response measurements

Spectral response (SR) or analogous quantum efficiency (QE) measurements are, as with I-V measurements, much simpler with SJ than with MJ solar cells.

First of all, the bias light needs to be adjusted to current limit the sub-cell to measure. For a dual junction a-Si cell this means blue-rich bias light is needed to limit the bottom cell and red-rich for the top cell. In addition to the bias light, bias voltage is required, because of the voltage shift in the operation points of the sub-cells. This ensures that the sub-cell operates at its I_{SC} and the correct SR is measured [3].

3 Experimental Arrangements

The method developed is done so with the LED-based solar simulator developed at CREST in mind, which is an ideal system for automatic measurements of MJ solar cells. The system uses 8 separately controllable LED colours and halogen light sources, thus delivering a very flexible spectral output. LEDs can be intensity varied with virtually no changes in the spectral output. Furthermore the complete system can be programmed to run fully automated. A published detailed description of the system can be found in [4].

4 Automated measurement approach

In this section, a measurement methodology for automated calibration of MJ solar cells is presented. In the future the system at CREST will be used to evaluate and validate the measurement procedures.

The target of this approach is that no further information of the MJ solar cell is required other than the number of junctions – and even that requirement might be removed in future systems. The approach is demonstrated with examples from a double junction a-Si solar cell with real and simulated data.

4.1 Basic measurement methodology

As shown in a simplified flow chart in Figure 1, the complete measurement routine can be separated into several smaller parts. These are described in the following sections.

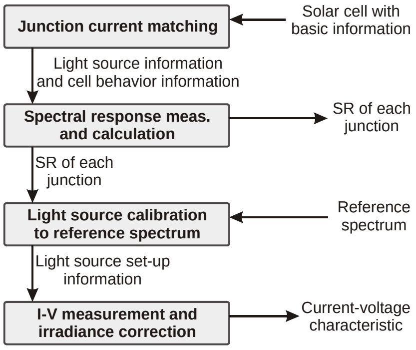

Figure 1: Simplified flow chart of solar cell characterisation for a reference spectrum

4.2 Junction current matching

The first step in the methodology is important for determining the simulator light setting needed to current match the device.

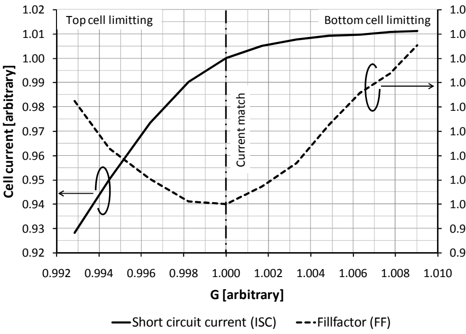

Figure 2: cell behaviour of an a-Si tandem device when changing UV light intensity

The best current matching process start point is a light source control set-up closest to the AM1.5G solar spectrum (if the cell has been optimised for this spectrum). From this point, the I_{SC} and fill-factor (FF) over light intensity (G) behaviour is measured by changing the intensity of the light source type expected to have most influence on one junction (e.g. ultraviolet (UV) for top cell) from zero to full intensity. If the resulting graph, as demonstrated on a-Si tandem cell with changing UV intensity in Figure 2, shows clearly two different slopes in short circuit behaviour, then the current match point has been crossed. In general, the fill factor is at its minimum at the point of junction matching, but exceptions occur if one of the cells has a low shunt resistance [2].

If I_{SC} over G is constant, the intensity is reset to its start value. In the case of a change of the limiting junction, the light intensity is set to the match point. This I_{SC} over G measurement process is then repeated for all light sources available. With the behaviour data of every light source on the cell it is then known at which points which junction is limiting and when the current is matched. This data is given to the next part for the spectral response measurements and fitting calculations.

4.3 Spectral response measurements

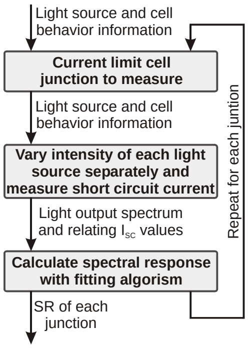

Figure 3: basic schematic flow diagram for spectral response measurements

Shown in Figure 3 are the three basic steps required for acquiring the SR of each junction separately. As visible in the diagram, the SR is not measured as it would be normally in the time consuming process of using a monochromator and measuring each point directly. Instead, the SR is estimated based on a fitting algorithm from a number of measured short circuit currents of the limiting cell at different incident spectra.

After current limiting the cell to measure, the intensity of each light source is independently increased and decreased. After every adjustment, the new I_{SC} with applied bias voltage is measured and the spectral output of the simulator recorded, which can be done by calculation if the spectrum of the light source is not changing with intensity.

The acquired I_{SC} and spectral output pairs are then fed into a minimising fitting algorithm, which fits newly calculated short circuit currents from the output spectra to the measured ones. The fitting can be done by changing the unknown values in either a polynomial function or an optical model relating to the device type (i.e. for a-Si solar cells according to the equations in [5]). A fitting with an optical model, can achieve much better results than with a polynomial function, but has the limitation that the measured device needs to be accurately described by the optical model used, thus this needs to be known in advance. However, it will certainly be applicable for similar devices such as from the same production. Figure 4 compares real SR of an a-Si double junction and the SR acquired by using an optical model in a Levenberg–Marquardt fitting algorithm.

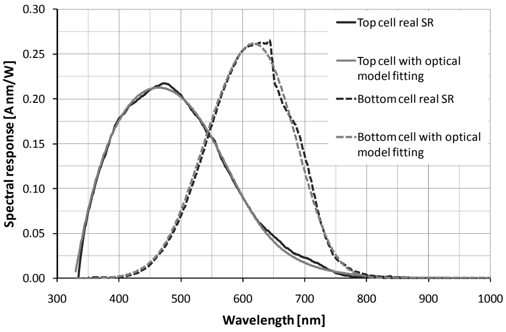

Figure 4: A-Si top and bottom cell SR derived by Levenberg–Marquardt fitting algorithm with optical model

4.4 Calibration to reference spectrum

If the simulator has more adjustable light sources than solar cell junctions, then it is important to calculate which of the light sources have the most influence on which junction. Those should then be used for adjusting the junction balance. The other light sources should be set to junction current match point and left as static constants in the linear equation system 1. This ensures that no negative intensity factors are found a solution.

The setting of the simulator light is then done as described in section 2.2. In the case that the desired intensity in the simulator cannot be set, the largest possible intensity with the same junction current balance is used. For determination of the series resistance, a further three irradiance settings are calculated and the light source irradiance settings acquired. The additional information is given to the next process part, which then triggers an irradiance correction.

4.5 I-V measurement, irradiance correction

The measurement of the I-V curve is fundamentally the same as it would be with a SJ solar cell. In cases where an irradiance correction was triggered, the process measures I-V curves at all given light settings, determines from the three I-V curves measured at lower irradiance with same current balance the average shunt resistance and corrects the I-V curve measured at highest intensity.

The result is an I-V curve measured at or corrected to reference spectrum conditions of the cell and the correct I_{SC}, V_{OC}, FF and power output has been acquired. Furthermore, correct efficiency also can be determined.

5 Conclusions and future work

An automatic measurement approach for multi-junction solar cell characterisation has been explained, which is applicable to single-junction solar cells and which uses a fitting method for calculating the spectral response. Thus, it eliminates the need for a specially designed spectral response measurement system or of reference cells for each junction with same response as the cell to test. This will save the user precious time and costs.

The method requires a multi-source solar simulator, some basic information about the test cell and a calibrated reference cell without zero response over the test cell spectral response band. It automatically delivers absolute spectral response of the test cell, I-V measurements at reference spectrum and can be enhanced for spectrometric characterisation.

The presented method will be embedded into the LED-based solar simulator developed at CREST. Measurement methods will be further developed and optimised. Final results will be verified with different devices against characterisations from traditional spectral response measurement systems and other simulators.

Acknowledgements

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