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IMPROVING THE ACCURACY OF SUNS-V_{OC} MEASUREMENTS USING SPECTRAL MISMATCH CORRECTION

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ABSTRACT

I_{SC}-V_{OC} curves measured by the Suns-V_{OC} method are widely used for solar cell characterization due to its unique feature of not being affected by series resistance effects. Although the accuracy of the Suns-Voc is good for standard silicon solar cells, care has to be taken when measuring solar cells whose spectral response differs significantly from that of the high-efficiency back contact silicon solar cell used as a reference cell due to a spectral mismatch.

Two options are possible in order to reduce this systematic measurement error. Firstly the spectral mismatch can be calculated and the measurement corrected for. Secondly, an appropriate filter can be introduced into the flash beam in order to adjust the spectrum of the flash.

With both methods a significant improvement in measurement accuracy can be achieved, as will be shown in this contribution.

INTRODUCTION

The Suns-V_{OC} measurement method, which was introduced by Sinton and Cuevas in 2000 [1], measures the illumination-dependent open-circuit voltage of solar cells and its precursors. During one measurement the illumination intensity is varied by three orders of magnitude by using a conventional photo flash, hence allowing a very fast measurement of the cell characteristics.

Several improvements have been suggested in order to enhance the measurement accuracy. The generalized evaluation, introduced by Kerr [2], is now widely used. It improves the accuracy for solar cells with high excess carrier lifetimes. Another improvement was the use of a temperature stabilized sample holder, which is now standard for new measurement systems. Also measurement artifacts due to a junction capacitance [3] or a high contact resistance [4] have been investigated.

Since the spectrum of the used xenon photo flash differs from the standard AM1.5G spectrum [5] (see Fig. 1), a significant spectral mismatch is expected for cells whose spectral response differs from that of the used high-efficiency silicon reference cell. This spectral mismatch will be investigated in this contribution by means of crystalline silicon thin-film solar cells. In addition, a very simple option will be presented, which improves the accuracy of the Suns-V_{OC} measurements significantly.

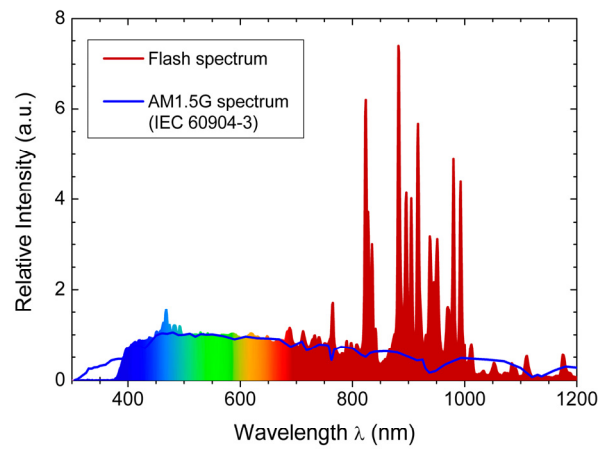

Fig. 1: Measured relative spectrum of the xenon photo flash which is used for illumination in the Suns-V_{OC} measurement setup. The spectrum is compared with the AM1.5G spectrum.

MEASUREMENT OF THE FLASH SPECTRA

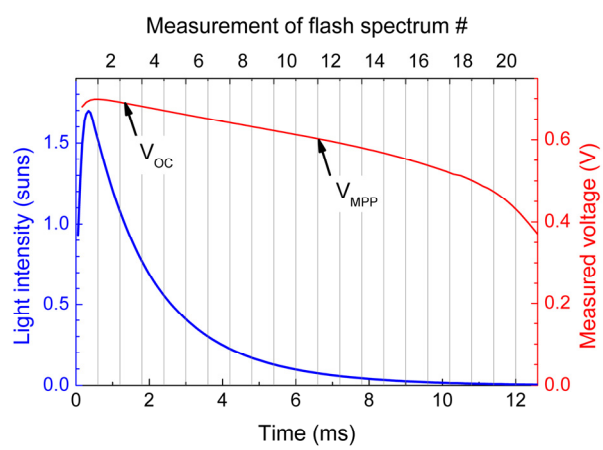

Fig. 2. Measurement curves for the measured light intensity (blue) and the cell voltage (red) during a typical Suns-V_{OC} measurement. Normally the V_{OC} is measured about 1 - 2 ms, the V_{MPP} 7 – 8 ms after the peak of the flash.

During the decaying edge of the flash in a typical Suns-V_{OC} measurement (shown in Fig. 2), the flash spectra have been measured for 20 consecutive time intervals. Each measurement took about 0.6 ms. These flash spectra have been acquired using single monochromator diode array spectroradiometers (SMDAS). Due to the fact that the SMDAS scans through the wavelength range sequently, the changing illumination conditions during one measurement had to be taken into account. Details about the used spectroradiometers can be found in [6].

Plots of the 3rd and the 11th flash spectrum are exemplary shown in Fig. 3. The intensity has been normalized to 1 in the wavelength range from 520 to 600 nm arbitrary. The red and infrared part of the spectrum is much higher for the 11th flash compared with the intensity of the 3rd one.

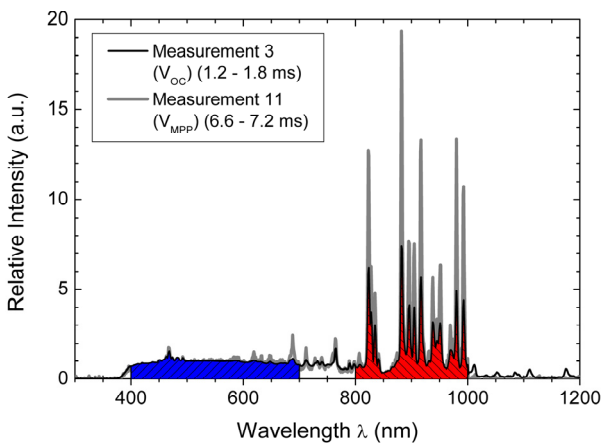

Fig. 3: Relative spectra of the xenon flash measured at different times of the decaying edge. The intensity has been normalized to 1 in the wavelength range from 520 to 600 nm. Blue and red shaded areas were integrated in order to visualize the change in the spectrum (see Fig. 4).

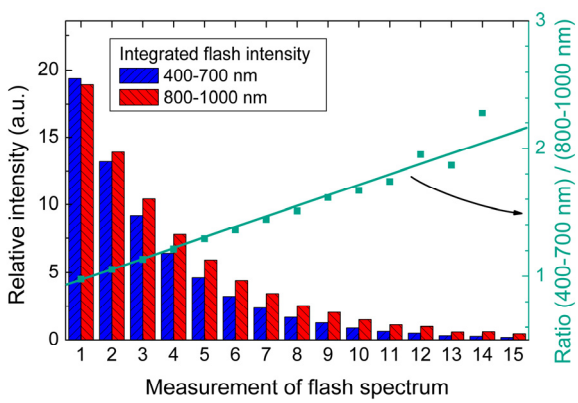

Fig. 4: Integrated flash intensities for the wavelength ranges 400 - 700 nm (blue) and 800 – 1000 nm (red). The ratio of these integrated flash intensities is plotted on the right, showing the increasing relative intensity of the red and infrared part of the spectrum.

In order to access this change in spectral intensity of the different flashes more easily, two integrals (one from 400 – 700 nm and one from 800 – 1000 nm) have been computed for all flashes (see Fig. 4). This analysis shows that the red and the infrared part of the spectrum gets stronger (compared to the blue and green part of the spectrum) the lower the absolute flash intensity is.

This means that not only the xenon flash spectrum differs from the AM1.5G spectrum, but also that the flash spectrum changes significantly throughout the Suns-V_{OC} measurement, resulting in an intensity-dependent spectral mismatch factor.

CRYSTALLINE SILICON THIN-FILM SOLAR CELL

A high-efficiency silicon solar cell is used in the Suns-V_{OC} measurement setup for determining the actual light intensity. This reference cell is protected by a plastic cover. The measured spectral responses are shown in Fig. 5.

Since the expected spectral mismatch is more severe for solar cells whose spectral response differs from that of the used reference cell, crystalline silicon thin-film solar cells without optical confinement have been investigated exemplarily.

The cells investigated here are epitaxially grown on highly-doped Czochralski (Cz) material. In detail, the cells consist of a 2 µm thick p^+, a 20 µm thick p and a 1 µm thick n^+ layer on top of the substrate. The cell process is described elsewhere [7]. The spectral response of one of these cells is also shown in Fig. 5.

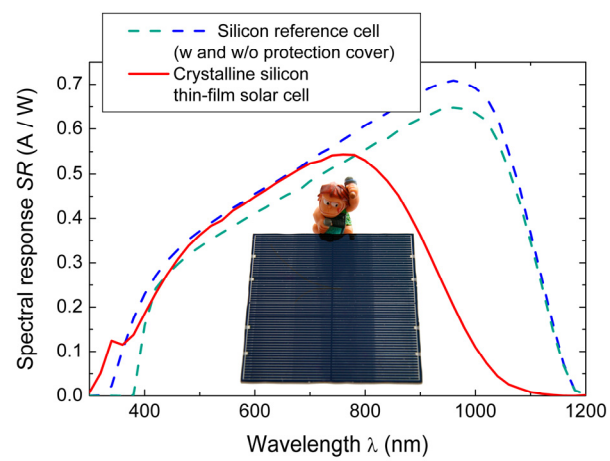

Fig. 5: Measured spectral responses of the crystalline silicon thin-film solar cell and the high-efficiency silicon reference cell (with and without protection cover). The insert shows a photograph of the investigated thin-film cell.

SPECTRAL MISMATCH CORRECTION

This deviation of the flash spectrum from the standard spectrum AM1.5G in combination with different spectral responses of reference cell and sample, leads to a spectral mismatch M, which can be calculated according to [8] as:

$$M = \frac{\int_{\lambda_1}^{\lambda_2} e_{\mathrm{AM1.5G}} \cdot sr_{\mathrm{Refcell}} \cdot d\lambda \cdot \int_{\lambda_1}^{\lambda_2} e_{\mathrm{Flash}} \cdot sr_{\mathrm{Sample}} \cdot d\lambda}{\int_{\lambda_1}^{\lambda_2} e_{\mathrm{Flash}} \cdot sr_{\mathrm{Refcell}} \cdot d\lambda \cdot \int_{\lambda_1}^{\lambda_2} e_{\mathrm{AM1.5G}} \cdot sr_{\mathrm{Sample}} \cdot d\lambda}, \quad (1)$$

where $e(\lambda)=E(\lambda)/E(\lambda_0)$ are relative spectra (of the flash and AM1.5G, respectively) related to an arbitrary wavelength λ_0 and $sr(\lambda)=SR(\lambda)/\mathrm{SR}(\lambda_0)$ are relative spectral responses (of the reference cell and the sample, respectively). From this knowledge, the corrected light intensity $I_{\mathrm{corrected}}$ for the sample can be calculated as

$$I_{\mathrm{corrected}} = M \cdot I_{\mathrm{measured}} \quad . \quad (2)$$

Having measured the intensity-dependent flash spectra and the spectral responses of the reference cell and the thin-film cell, we were able to calculate the spectral mismatch factor M (see Fig. 6). The calculated mismatch varied from 0.86 to 0.78 for the first 15 flash spectrum measurements, meaning that the light intensity measured by the reference cell is 16 – 28% higher than the light intensity the sample actually "sees".

The impact of this large discrepancy in illumination intensity on the open-circuit voltage can be estimated using the one-diode model (for a mismatch factor 0.8):

$$\begin{aligned} \Delta V_{OC} &= \frac{kT}{q}\ln\left(\frac{J_{SC}}{J_0}\right) - \frac{kT}{q}\ln\left(0.8\frac{J_{SC}}{J_0}\right) \\ &= -\frac{kT}{q}\ln(0.8) = 5.8\ \mathrm{mV} \quad . \end{aligned} \quad (3)$$

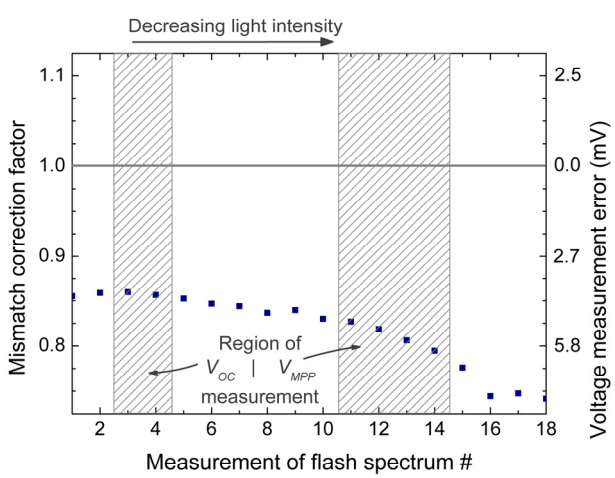

Fig. 6: Calculated spectral mismatch factors for the crystalline silicon thin-film solar cell based on the measured flash spectra and spectral responses. Typical measurement regions for V_{OC} and V_{MPP} are shaded. The voltage measurement error is calculated using the one-diode model (eq. (3)).

These calculated mismatch factors can be used to correct the measured light intensity of the reference cell using equation (2) in order to improve the measurement accuracy.

SHORT PASS FILTER

Another, much easier way to reduce the spectral mismatch error and hence improve the measurement accuracy of the Suns-V_{OC} measurement setup is achieved by shaping of the flash spectrum by using an additional filter. This filter should reduce the red and infrared part of the flash spectrum in order to get the deviations compared to the AM1.5G spectrum as small as possible.

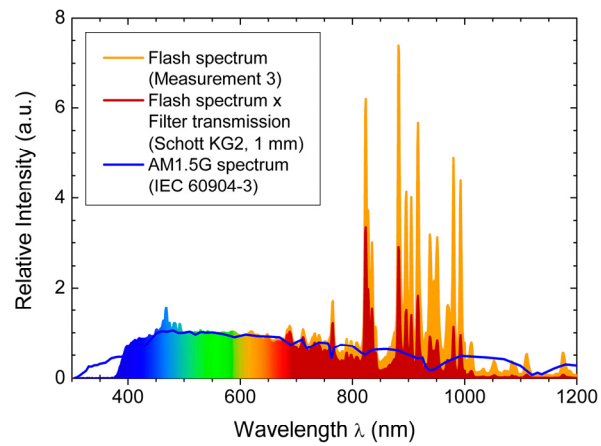

Fig. 7: Relative spectra of the xenon flash including a 1 mm thick KG2 short pass filter. As intended the inflated red and infrared part of the spectrum are attenuated.

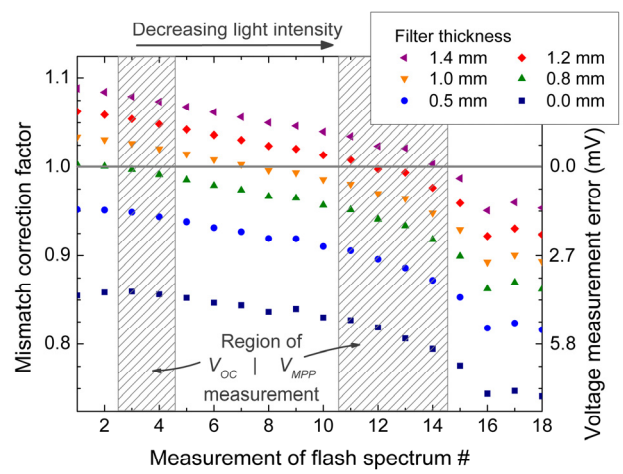

Fig. 8: Calculated mismatch factors of the investigated crystalline silicon thin-film cell for different thicknesses of a KG2 short pass filter. Typical measurement regions for V_{OC} and V_{MPP} are shaded. The voltage measurement error is calculated using the one-diode model (eq. (3)).

Our simulations have shown that a KG2 short pass filter is best suited (see Fig. 7). Based on measured transmissions of a 1.2 mm thick Schott KG2 filter, spectral mismatch calculations have been carried out for different filter thicknesses (Fig. 8).

Since this type of correction can not account for the changing spectrum throughout the measurement, the resulting mismatch factor is not constant. A filter thickness of 1 mm is best suited to significantly reduce the spectral mismatch error for the V_{OC} and also for the V_{MPP} measurement (where the pseudo fill factor is deducted from).

Due to the fact that this kind of filter reduces the amount of photons in the 1000 – 1150 nm range, care has to be taken if the experiment is particularly sensitive to this region, for example measurements on cells with a band gap in the 900 – 1000 nm region. No drawback is expected (nor was it observed) for typical silicon based solar cells.

RESULTS

A calibrated steady state IV measurement of the crystalline silicon thin-film cell investigated here was carried out at the Fraunhofer ISE CalLab. The parameters for V_{OC} and fill factor (*FF*) are listed in Tab. 1 together with the parameters obtained with the Suns-V_{OC} measurement method.

The uncorrected Suns-V_{OC} measurement had a deviation of 6 mV for V_{OC}. After we realized the intensity-dependent spectral mismatch correction, the error in V_{OC} was reduced to 2 mV. Also the pseudo fill factor (pFF) changed by 0.7% absolute. Please note that the pFF is expected to be higher than the FF from the steady-state IV-measurement since the Suns-V_{OC} does not account for series resistance effects.

The same excellent results were obtained for the static correction with an additional 1 mm thick KG2 short pass filter. These experimental results perfectly agree with the calculated values using the one-diode model using eq. (3).

In addition, the same corrections were carried out for other types of silicon based solar cells. Multicrystalline solar cells showed the same trends with a reduced mismatch error with either of the two methods presented here, whereas the absolute errors for V_{OC} and *pFF* were smaller compared to the thin-film sample presented here.

Furthermore results for a high-efficiency PERL silicon solar cell are plotted in Tab. 2. For this kind of cells with a high open-circuit voltage the generalized evaluation [2] can not be neglected due to the high lifetime of the charge carriers. The use of an additional KG2 short pass filter does not improve the measurement accuracy, though it does not interfere with the measurement either.

SUMMARY

In this contribution the impact of a spectral mismatch on Suns-V_{OC} measurements was investigated. Crystalline silicon thin-film solar cells were analyzed in order to ascertain the impact of such spectral mismatches.

Tab. 1: Measurement results for the investigated crystalline silicon thin-film solar cell. Calibrated measurements were carried out at the Fraunhofer ISE CalLab. Results for both correction methods are shown.

	Suns-V_{OC} uncorrected	**Suns-V_{OC} mismatch corrected**	**Suns-V_{OC} with KG2 filter**	**ISE CalLab measurement**
V_{OC} (mV)	649	653	654	655 (± 3)
***pFF* (%)**	81.2	81.9	81.6	
***FF* (%)**				79.9 (± 0.6)

Tab. 2: Suns-V_{OC} and steady state results for a high-efficiency (η = 21.8 %) PERL silicon solar cell. The impact of the generalized evaluation can be seen. The additional KG2 filter does not change the results at all, showing that there is no drawback of such a filter.

	Suns-V_{OC} uncorrected	**Suns-V_{OC} general. eval.**	**Suns-V_{OC} general. eval. & KG2 filter**	**ISE steady state measurement**
V_{OC} (mV)	689	686	686	686
***pFF* (%)**	85.4	83.2	83.4	
***FF* (%)**				79.8

In order to calculate the correction factors for the Suns-V_{OC} measurements, reliable measurements of the intensity-dependent spectra of the used xenon flash were carried out as well as accurate measurements of the spectral responses of the used high-efficiency silicon reference cell and the investigated samples. The measurement results of the open-circuit voltage were significantly improved using this mismatch correction. However, the spectral response for every investigated sample has to be known.

Another, much easier approach to minimize the mismatch error, is the use of an adequate short pass filter in order to form the spectrum of the used xenon flash. With a 1 mm thick KG2 short pass filter, the same excellent results were obtained as with the calculated mismatch factors. No drawbacks are expected when using this type of filter with typical silicon based solar cells.

ACKNOWLEDGEMENTS

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