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A NEW TOOL TO MEASURE MONOLITHIC MULTI JUNCTION SOLAR CELLS WITH UP TO SIX SUBCELLS

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ABSTRACT: New monolithic multi-junction cell concepts with more than three subcells are a challenge for a precise light IV-curve characterization. The available sun simulator tools are not suitable for the characterization of these devices. Therefore, a new six channel sun simulator was set up to measure and characterize monolithic solar cells with up to six subcells. This paper presents main benchmark data of the new simulator, like uniformity and spectrum. Calibrated light IV-curves of four- and six-junction solar cells are shown.
Keywords: Characterization, Calibration, quadruple-junction, sixtupel-junction

1 INTRODUCTION

Lattice matched III-V triple-junction solar cells are the state-of-the-art device for space and terrestrial concentrator applications. Several advanced multi-junction solar cells concepts are currently investigated to further increase the efficiency. One promising approach is to increase the number of stacked subcells. At present, multi-junction solar cells with four, five and six subcells are under development, e.g. [1]-[5]. Figure 1 shows a scheme of the structure as well as the external quantum efficiency (EQE) of a six-junction solar cell, which was manufactured and characterized at Fraunhofer ISE.

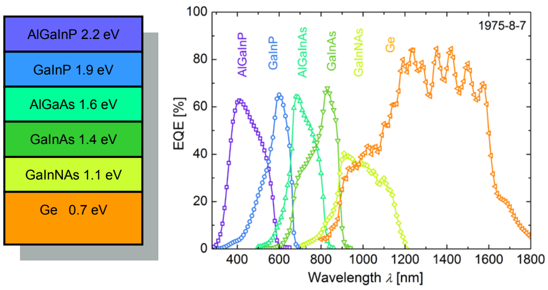

Figure 1: Schematic structure of a monolithic six-junction solar cell under development at Fraunhofer ISE (left). EQE of a six-junction solar cell manufactured and characterized at Fraunhofer ISE (right).

These advanced solar cell concepts pose new challenges on solar cell characterization techniques. For triple-junction solar cells calibration routines based on a generalization of the spectral mismatch correction are well established [6],[7] and corresponding sun simulators are available. At Fraunhofer ISE a three-source sun simulator is used for the calibrated measurement of the one-sun light IV-curve of multi-junction solar cells with up to three junctions. In order to independently adjust the photocurrent of each subcell to its desired value under standard testing conditions, the same number of spectrally different light sources which are adjustable in their intensity is required. In consequence, the three-source simulator cannot be used for calibrated IV-curve measurements of solar cells with more than three subcells. Therefore, the new and innovative six-channel solar simulator "X-Sim" was built by the company Aescusoft GmbH in close cooperation with Fraunhofer ISE. The structure and the optical properties of the illumination unit, the measurement procedures and first measurement results are presented in this paper.

2 SETUP

Figure 2 shows a schematic of the X-Sim simulator. It consists of an illumination unit that can be adjusted in height and a measurement unit. The measurement unit is comprised of a temperature controllable measurement chuck as well as of measurement electronics and software for controlling the system.

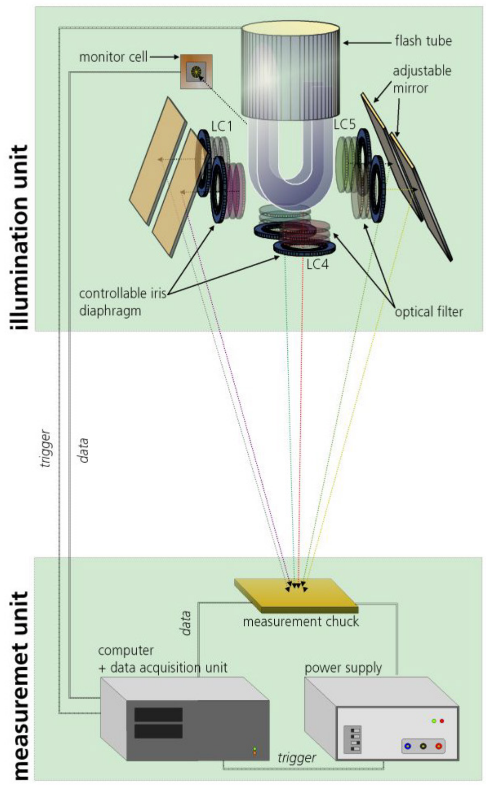

Figure 2: Schematic structure of the sun simulator X-Sim with all important elements of the illumination unit and the measurement unit, which are described in detail in the text.

2.1 IlluminationUnit

The key element of the X-Sim sun simulator is the illumination unit. The basic idea is to use only one single light source and to form six "**L**ight **C**hannels" (LCs) out of it, whose intensity can be adjusted independently. Each light channel is equipped with a set of optical filters to separate the simulator spectrum into six different spectral bands. The advantage of using only one light source is that possible small fluctuations in intensity of the used flash tube have the same effect on each light channel, i.e. the relative course of the simulator spectrum is not altered. Thus, the ratio of the subcells' currents to each other will not be influenced and a standard intensity correction can be applied. A xenon flash tube is uses as light source. Its temporal pulse profile shows a 1.5 ms intensity plateau with an intensity variation of less than ±1 %. The six light channels are arranged around the flash tube (see Figure 2). Each light channel is equipped with an iris diaphragm for intensity control and one filter set to divide the spectrum of the xenon flash into six separate spectral regions. The transmission of these filter combinations is shown in Figure 3.

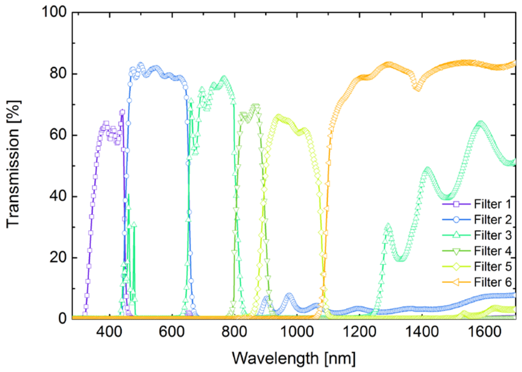

Figure 3: Transmission curves of the filter combinations applied to the six light channels of the sun simulator X-Sim. The spectral ranges of the light channels were chosen to match the subcells' EQE of a typical Fraunhofer ISE six-junction cell (see Figure 2)**.**

The transmission curves of the individual light channels are sharply separated from each other. The wavelength ranges of the individual filters were chosen to match the subcells' EQE of a Fraunhofer ISE six-junction solar cell. However, the filters can be modified in order to adjust the wavelength ranges to other solar cell designs.

The intensity of each light channel and thereby each spectral range can be adjusted separately via computer controllable iris diaphragms. The light passing through the individual light channel is directed towards the measurement plane via independently adjustable mirrors.

In addition, the illumination unit is equipped with a GaAs-monitor cell which is used for measuring the temporal irradiation profile of the flash. The signal of the monitor cell is used for an irradiation correction according to [8]. Within a single measurement (i.e. one flash), the intensity varies by less than ±1 %. Within 100 successive measurements, the intensity was found to vary by ±1.2 % (mean intensity flash to flash).

2.2 Measurement Unit

The cell under test is placed on a temperature controllable measurement chuck and is fixed by vacuum. In the case of bare cells, the measurement chuck serves as rear contact also.

A four-quadrant power supply serves as variable electrical load in order to sweep the IV-curve. The current is determined as voltage drop upon a precision resistor. The voltage is measured directly at the terminals of the cell (four wire technique). For data collection two fast National Instruments (NI) data acquisition cards are used. The IV-curve can be measured in forward mode (voltage sweep from I_{SC} to V_{OC}) and/or in backward mode (voltage sweep from V_{OC} to I_{SC}). Additionally the IV-curve can be measured in the so-called multi-flash mode, in which a fixed voltage is applied to the cell during one flash hence generating one single point on the IV-curve. In the multi-flash mode, the full IV-curve measurement is typically obtained after 20 to 40 flashes.

The system uses a central software trigger that controls the flash, the data acquisition and the variable electric load for sweeping the IV-curve of the device under test.

3 COMMISSIONING

After installation the simulator has been studied extensively. The work focused primarily on the uniformity of irradiance in the measurement plane as well as on the spectral characteristic of the X-Sim sun simulator. Additionally the intensity of the light channels has been calibrated with a reference solar cell.

3.1 Uniformity of Irradiance

The mirrors of the illumination unit were adjusted by means a solar cell array for monitoring the intensity distribution in the measurement plane. The array consists of 64 silicon cells with an area of 1 cm² each. They are distributed on an area of 15 cm x 15 cm. The uniformity of irradiation was measured separately for each light channel as a function of aperture opening. The uniformity plots of all six light channels for an aperture opening of 80 % are exemplarily shown in Figure 4. The corresponding non-uniformities calculated according to [9] are given in Table I. For a cell under test whose area deviates from the reference solar cell used (area usually 2 cm x 2 cm) a non-uniformity correction factor can be determined. These corresponding correction factors for an aperture opening of 80 % are also provided in Table I, respectively.

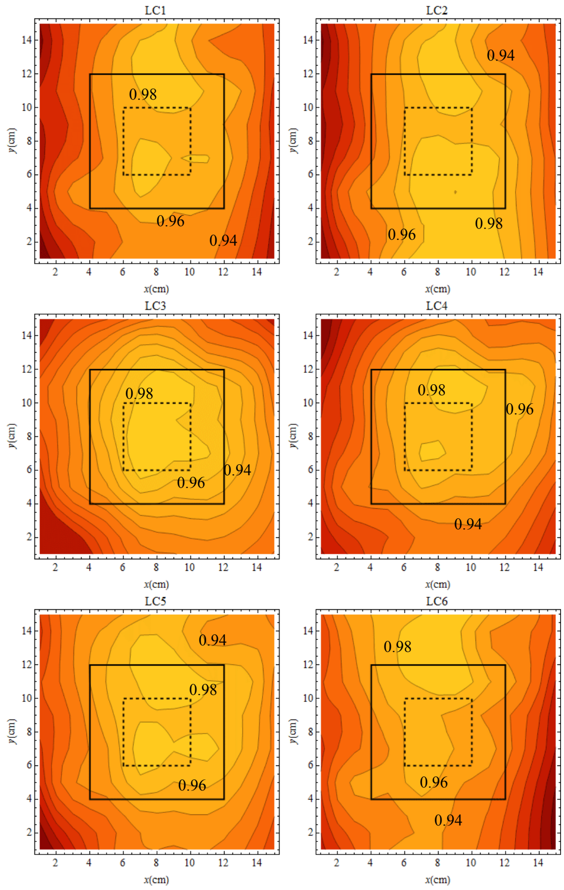

Figure 4: Normalized intensity profiles of the individual light channels measured separately with a diaphragm opening of 80 %. The dashed line covers an area of 4 cm x 4 cm, the solid line covers an area of 8 cm x 8 cm.

Table I: Non-uniformity and correction factors for all six light channels and an aperture opening of 80 %.

	Non-Uniformity 4 cm x 4 cm (8 cm x 8 cm) [%]	Correction factor 4 cm x 4 cm (8 cm x 8 cm)
LC1	1.4 (3.9)	1.002 (1.012)
LC2	1.9 (4.2)	1.003 (1.013)
LC3	1.6 (5.5)	1.005 (1.028)
LC4	1.5 (4.7)	1.003 (1.017)
LC5	1.6 (5.1)	1.003 (1.016)
LC6	1.4 (4.1)	1.002 (1.011)

The individual light channels show different uniformities of irradiance. Additionally the uniformity of irradiance depends on aperture opening. Thus, the non-uniformity and correction factors were determined for each light channel in dependence of aperture opening. Figure 5 shows the correction factors of each light channel in dependence of the aperture opening. In this case an area of 8 cm x 8 cm is assumed for the cell under test whereas the reference cell has an area of 2 cm x 2 cm. During the measurement of typical multi-junction solar cells with three to six subcells under AM0 conditions aperture openings between 70 % and 85 % are usually used.

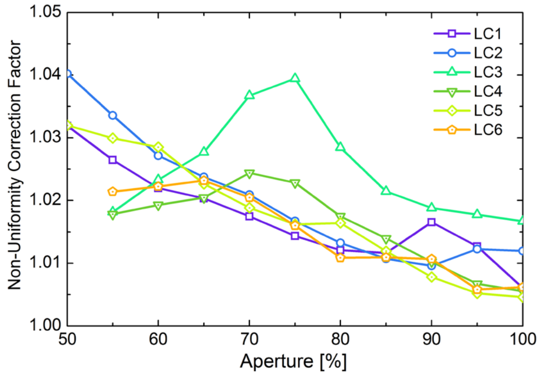

Figure 5: Intensity correction factors for a cell under test with an area of 8 cm x 8 cm and a reference cell with an area of 2 cm x 2 cm as a function of aperture opening for all six light channels.

Except for light channel three the correction factors decrease with increasing aperture opening. For the above mentioned case correction factors between 1.005 and 1.04 have been determined.

3.3 Spectral Distribution

The spectral distribution of the six light channels was measured with a single monochromator diode array spectroradiometer setup as described in [10] and within the 1.5 ms intensity plateau of the flash. Figure 6 shows the spectral distributions of the individual light channels as well as a measurement of the flash tube itself without filtering or mirror reflection.

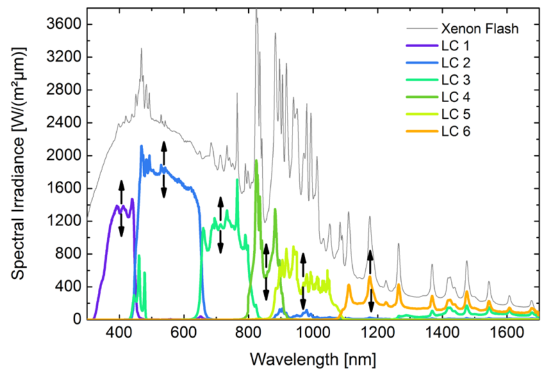

Figure 6: Measured spectral distributions of the six light channels of the sun simulator X-Sim and of the flash tube without filtering. The light channels were equipped with filter combinations as in Figure 3.

3.4 Intensity Calibration of the Simulator

In order to calibrate the relation between aperture opening and absolute spectral irradiance level on the test plane a primary silicon reference cell with known absolute spectral response (SR) was used. For the intensity calibration of the sun simulator X-Sim IV-curves of the reference cell were measured for each individual light channel for aperture opening steps of 10 %. To obviate transient effects the IV-curves were measured twice; forward ($I_{sc} \rightarrow V_{oc}$) and backward ($V_{oc} \rightarrow I_{sc}$) and the average were calculated. This results in 122 IV-curve measurements in total (two IV-curves per setting, six light channels, 10 different aperture openings per light channel and two IV-curves with all apertures closed). The result of the intensity calibration of the aperture opening is shown in Figure 7. There, the measured current of the silicon reference cell TF31-3 is shown as a function of aperture opening for all six light channels. It can be observed that the relation between aperture opening and solar cell current is not strictly linear.

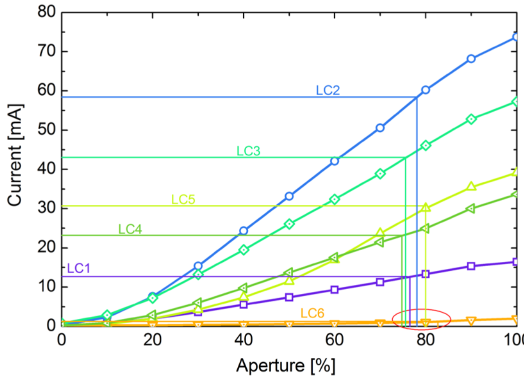

Figure 7: Correlation between aperture opening and the current of the silicon reference cell TF31-3. The additionally drawn thin lines represent the results of a spectral correction (see next section) for the Fraunhofer ISE six-junction solar cell 2720-1-7 under AM0 conditions.

Subsequently the measured current values of the silicon reference cell in Figure 7 can be used to normalize the spectral distribution of the light channels to absolute values. A linear interpolation is performed between two measured aperture openings.

4 CHARACTERIZATION OF MULTI-JUNCTION SOLAR CELLS

4.1 Spectral Correction

The spectral correction for multi-junction cells is a generalization of the spectral mismatch correction. For the calibration it is required that in each individual subcell i the generated photocurrent under the simulator $j_{sim}^{TC,i}$ equals the current $j_{ref}^{TC,i}$ of subcell i under the reference spectrum.

$$j_{sim}^{TC,i} = j_{ref}^{TC,i} \quad i = 1,\dots, z \quad z\text{: number of subcells} \qquad (1)$$

This can only be achieved if not only the intensity of the simulator but also the relative course of the simulator's spectrum can be modified. In the present case of the sun simulator X-Sim, six light channels are used to fulfill the above requirement. The main assumption of the spectral correction procedure applied is, that in each subcell the currents generated by the individual light channels sum up to the total current of this subcell under the simulator. The spectral correction procedure is described in more detail in [11]. The current of junction i generated by light channel k can be represented by the integral over the product of absolute spectral response SR^i of subcell i and absolute spectral irradiance $E_k(\lambda)$ of light channel k. In most cases the absolute spectral response is not known, and thus is written as $c^i sr^i(\lambda)$ with normalization factor c^i of relative spectral response sr^i.

As the correct settings of the light sources and thus the simulator are not known right from the beginning, an adjustment factor A_k is introduced for each light source. Thus the above requirement from equation (1) can be rewritten to:

$$A_1 c^1 \int sr^1(\lambda) \cdot e_{sim,1}(\lambda)\, d\lambda + \cdots + A_6 c^1 \int sr^1(\lambda)\, e_{sim,6}(\lambda) \cdot d\lambda = c^1 \int sr^1(\lambda)\, E_{ref} \cdot d\lambda \qquad (2)$$

As can be seen from equation (2), the factors c_1 cancel out. Equation (2) can then be rewritten for each subcell, thus leading to the following system of linear equations (3):

$$\begin{aligned} & A_1 \int sr^1(\lambda) \cdot e_{sim,1}(\lambda)\, d\lambda + \cdots + A_6 \int sr^1(\lambda)\, e_{sim,6}(\lambda) \cdot d\lambda = \int sr^1(\lambda)\, E_{ref} \cdot d\lambda \\ & \dots \\ & A_1 \int sr^6(\lambda) \cdot e_{sim,1}(\lambda)\, d\lambda + \cdots + A_6 \int sr^6(\lambda)\, e_{sim,6}(\lambda) \cdot d\lambda = \int sr^6(\lambda)\, E_{ref} \cdot d\lambda \end{aligned} \qquad (3)$$

The solution of this linear system of equations (3) – the A_k factors – leads to the absolute spectral irradiance $E_k(\lambda)$ of the individual light channel k: $A_k e_k(\lambda)$. The intensity of the individual light channels, i.e. aperture opening of the light channel, is fineventually set with the help of the intensity calibration shown in Figure 7. In Figure 8 the outcome of the spectral correction for the Fraunhofer ISE six-junction cell 2720-1-7, i.e. the simulator spectrum used for the calibration of this cell is shown together with the reference spectrum AM0 [12].

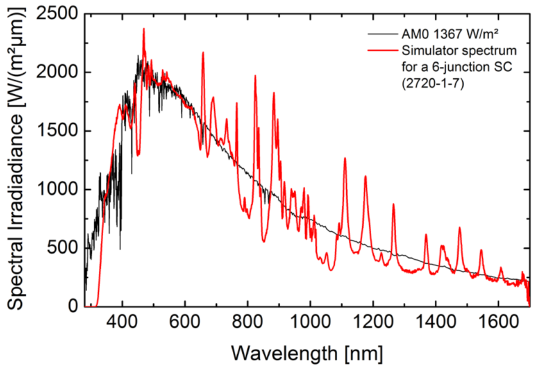

Figure 8: Reference spectrum AM0 [12] and the simulator spectrum of the X-Sim after performing a spectral correction for the six-junction solar cell 2720-1-7.

4.2 Calibrated IV-Curve Measurements

In order to verify the measurements at the X-Sim sun simulator, a measurement comparison has been performed using a triple-junction solar cell. The triple-junction cell has initially been calibrated under AM0 conditions at the established three-source simulator MuSim at ISE CalLab [13], [14]. Afterwards the cell has been measured at the X-Sim sun simulator. The IV-curves measured at the two different sun simulators are shown in Figure 9.

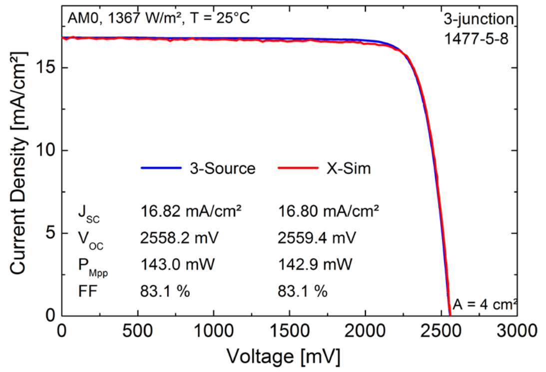

Figure 9: Comparison of IV-curve measurements under AM0 conditions (1367 W/m², T = 25 °C) of a GaInP/GaInAs/Ge lattice matched triple-junction cell 1477-5-8. One measurement was obtained using the three-source simulator MuSim and the other using the new six-source simulator X-Sim. At the X-Sim two IV-curves have been measured – forward ($I_{SC} \rightarrow V_{OC}$) and backward ($V_{OC} \rightarrow I_{SC}$). The displayed IV-curve for the X-Sim corresponds to the average of these two curves.

The comparison between the two sun simulators shows an excellent agreement. This proves that the developed X-Sim and the adapted calibration routines are now available to calibrate monolithic multi-junction solar cells with up to six subcells. Consequently, we have used the new solar simulator X-Sim to calibrate four-, five- and six-junction solar cells made at Fraunhofer ISE. Examples of calibrated IV-curve of a four- and a six-junction solar cell are shown in Figure 10 and Figure 11, respectively:

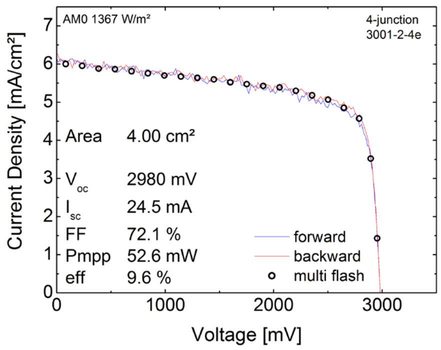

Figure 10: IV-curve measurement of the Fraunhofer ISE 4-junction solar cell 3001-2-4e under AM0 conditions performed with the new X-Sim sun simulator. The two curves swept during one flash in forward and backward mode show insignificant transient effects. In order to justify the averaging of these two curves a multi-flash measurement is also shown.

The IV-curves of the four-junction cell 3001-2-4e in Figure 10 show no indication of transient effects. A good agreement was found between full IV-curve measurement during one flash (forward and backward) and the IV-curve recorded in multi-flash mode.

Figure 11 shows measurement results of a six-junction cell (2720-1-7). Small transient effects were found for IV-curves swept in forward and in backward mode. The multi-flash measurement and the average of the forward and backward IV-curve show an excellent agreement.

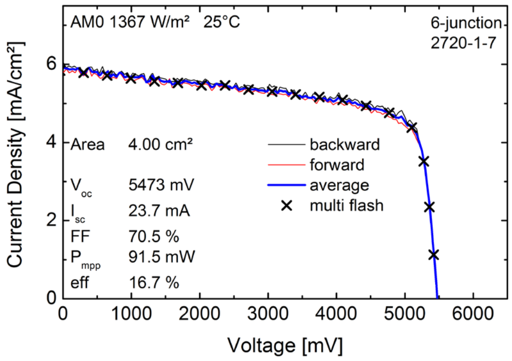

Figure 11: IV-curve measurement of the Fraunhofer ISE six-junction solar cell 2720-1-7 under AM0 conditions performed with the new X-Sim sun simulator (multiflash as well as the average of backward and forward).

The IV-curves in Figure 11 correspond to a calibrated IV-curve measurement of a six-junction cell. This is the first published calibrated IV-curve of a six-junction solar cell by Fraunhofer ISE. Uncertainty analysis for IV-measurements at the new sun simulator X-Sim has not yet been performed and will have to be matter of further research.

5 CONCLUSION AND OUTLOOK

A new sun simulator for calibrated IV-curve measurements of solar cells with up to six subcells has been presented. The X-Sim sun simulator set up is based on six individual light channels originating from only one single flash tube. Each light channel is equipped with a set of optical filters and an iris diaphragm. The optical filters separate the light channels into different spectral bands. The iris diaphragms are used for intensity variation of the light channels.

An analysis of the uniformity and the spectral distribution of the X-Sim sun simulator have been shown. The spectral correction procedure based on measurements of the spectrum of the light channels and a calibration of intensity with a reference cell were described. A measurement comparison with the established three-source sun simulator MuSim at ISE CalLab shows an excellent agreement for a lattice matched three-junction cell under AM0 conditions. Calibrated IV-curve measurements of four- and six-junction solar cells under AM0 conditions were carried out successfully and shown in this paper for the first time. A detailed uncertainty analysis will be performed in the future.

6 ACKNOWLEDGEMENTS

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