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A NEW PROCEDURE FOR THE ACCURATE INDOOR MEASUREMENT OF SOLAR-CELL I-V CHARACTERISTICS

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The present work describes and validates a method for the adjustment of light intensity in indoor solar-cell I-V tests. The procedure basically consists of the evaluation of the spectral-mismatch parameter as a function of light intensity before measuring. The simulator is set to the irradiance that produces a spectral-mismatch parameter equal to unity (or to some other desired value) and only then is the I-V curve taken. The main advantages are: no need to use very similar reference and test cells, direct extraction of the right whole I-V curve without cell models and ease to measure under different light intensities.

Keywords: Solar simulator; Measurement; Indoor

1. INTRODUCTION

Solar-cell research and development, fabrication and quality control require a suitable device characterisation. Among a number of useful cell-assessment tools, two kinds of measurements are basic in photovoltaics: I-V characteristics and spectral response. While the latter is an important help even when only relative values are obtained (which is often the case, owing to experimental limitations), the determination of the current-*vs.*-voltage dependence under well

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controlled illumination conditions is absolutely crucial. In addition to the adequate temperature control and measurement, and to the corresponding translation of data to standard test conditions (STC), the proper control of both light intensity (integrated irradiance) and light spectrum (relative spectral irradiance) is of primary importance for obtaining consistent and meaningful results.

Outdoor measurements using natural sunlight are widely used, but not always possible. Furthermore, they have limitations mainly based on the difficulty to modify light-source features. Indoor tests with special solar simulators are, therefore, quite popular and, in many cases, the only possibility to assess cell performance.

A well known procedure [1], which will be called "conventional" herein, describes the steps to follow. This widely used method imposes, however, a number of requirements, such as:

- The light source must be either the sun or a simulator providing class A, B or C simulation [1], defined by how close the actual solar-simulator spectrum matches the reference one ([3, 4]).
- The reference cell must have a spectral response highly similar to that of the test cell.
- Beside corrections for temperature, the short-circuit current must be corrected by dividing it by the calculated spectral-mismatch parameter M [5].
- Spectral-mismatch correction of the whole I-V curve has to be done subsequently on the basis of a certain model, which holds for certain standard cells, but not for any cell.
- Only measurements done in conditions such that the spectral-mismatch parameter is 1.00 ± 0.02 are valid [1]. This requirement imposes serious restrictions, especially when devices of very different spectral responses must be characterised.

The last two limitations are particularly relevant for the development of new kinds of devices.

A new procedure is proposed herein being able to produce I-V curves needing neither spectral-mismatch corrections nor theoretical cell models. The short-circuit currents derived directly from these I-V curves are right values with accuracies similar to those of the conventional procedure. The rest of the cell parameters (open-circuit voltage, fill factor *etc.*) can also be obtained at once from these plots without any further spectral corrections. The reference cell used for calibration need not match the test cell in spectral response. It may even be of a different technology.

2. METHOD DESCRIPTION

The key point of the procedure proposed is to adjust the simulator in such a way that the light it generates has the same effect on the cell under test as that which would be produced by the reference illumination desired. Starting from the equations used by Osterwald [6], the following expression can be written:

$$\frac{I_{SIM}^{TC}}{I_{REF}^{TC}} = M \frac{I_{SIM}^{RC}}{I_{REF}^{RC}} \tag{1}$$

where I represents short-circuit current, TC test cell, RC reference cell, SIM solar simulator and REF reference spectrum in STC. M is the spectral mismatch parameter as defined in [5]:

$$M \equiv \frac{\int_0^\infty e_{SIM}(\lambda) S^{TC}(\lambda) d\lambda \int_0^\infty e_{REF}(\lambda) S^{RC}(\lambda) d\lambda}{\int_0^\infty e_{REF}(\lambda) S^{TC}(\lambda) d\lambda \int_0^\infty e_{SIM}(\lambda) S^{RC}(\lambda) d\lambda} \tag{2}$$

where e represents spectral irradiance (in mW $\mathrm{cm}^{-2}\,\mathrm{nm}^{-1}$, *e.g.*) and S represents spectral response (in A W^{-1}, *e.g.*). The usefulness of this expression resides in that all functions appear once in the numerator and once in the denominator. There is, thus, no need to know spectral irradiances and spectral responses absolutely. Only their relative values are necessary for calculating the spectral-mismatch parameter.

The conventional method involves:

(1) Measuring the reference-cell short-circuit current I_{SIM}^{RC} corresponding to a simulator integrated irradiance very close or equal to 1 sun ($76.8\,\mathrm{mW\,cm}^{-2}$ for direct normal irradiance AM1.5D, $100\,\mathrm{mW\,cm}^{-2}$ for normalised global irradiance AM1.5G *etc.*). The relative spectral irradiance of the simulator for this particular intensity must be known.

(2) Measuring the I-V characteristic of the test cell when put in the position previously occupied by the reference cell and leaving the simulator integrated irradiance unchanged.

(3) Calculating the spectral-mismatch parameter M by means of Eq. (2).
(4) Deriving I_{REF}^{TC} from Eq. (1).

The new method, otherwise, involves calculating the spectral-mismatch parameter as a function of integrated irradiance before measuring, and then finding the value of the simulator irradiance for which the ratio $I_{SIM}^{TC}/I_{REF}^{TC}$ is equal to unity (or to any desired value).

The following defining expression can be written for any test cell:

$$F(E_{SIM}) \equiv \frac{I_{SIM}^{TC}(E_{SIM})}{I_{REF}^{TC}} \tag{3}$$

where E_{SIM} is the simulator integrated irradiance and the non-dimensional factor $F(E_{SIM})$ is the number of equivalent reference-spectrum suns on the test cell when this is illuminated having set the simulator to give an integrated irradiance E_{SIM} on the test plane. This definition leads to another one:

$$E_{EFF}(E_{SIM}) \equiv F(E_{SIM}) \int_0^{\infty} e_{REF}(\lambda) d\lambda \tag{4}$$

E_{EFF} being called the *effective integrated irradiance* (abbreviated *effective irradiance*) on the test cell with respect to spectrum e_{REF}, when the cell is illuminated with a particular simulator adjusted to a particular value of its integrated irradiance E_{SIM}.

E_{EFF} is a magnitude having irradiance dimensions ($mW\,cm^{-2}$, for example), associated with a particular simulator, a particular reference spectrum and a particular test cell, whose defining feature is that when its value is equal to the integrated irradiance associated with the reference spectrum ($100\,mW\,cm^{-2}$ for 1 sun global AM1.5G, *e.g.*), the effect (in terms of short-circuit current) of the simulator on the test cell is equal to that caused by the reference spectrum itself. This is also valid for any integrated irradiance wished. The method proposed implies finding the value of E_{SIM} needed to obtain a particular value of E_{EFF} (typically $100\,mW\,cm^{-2}$).

From Eqs. (1), (2) and (3) the following expressions hold:

$$F(E_{SIM}) = F_1(E_{SIM}) \cdot F_2(E_{SIM}) \tag{5}$$

$$F_1(E_{SIM}) = \frac{\int_0^\infty e_{SIM}(\lambda, E_{SIM}) S^{TC}(\lambda) d\lambda}{\int_0^\infty e_{REF}(\lambda) S^{TC}(\lambda) d\lambda} \tag{6}$$

$$F_2(E_{SIM}) = \frac{\int_0^\infty e_{REF}(\lambda) S^{RC}(\lambda) d\lambda}{\int_0^\infty e_{SIM}(\lambda, E_{SIM}) S^{RC}(\lambda) d\lambda} \cdot \frac{I_{SIM}^{RC}(E_{SIM})}{I_{REF}^{RC}} \tag{7}$$

It should be noted that although the simulator spectral irradiance to be used in these equations is only relative, its dependence on the integrated irradiance E_{SIM} has to be taken in consideration, because the spectral content of the light of a simulator varies with the current flowing through its lamp or lamps.

The method proposed consists of the following steps:

- Simulator calibration

(1) Putting a reference cell on the test plane.
(2) Adjusting the simulator irradiance E_{SIM} to a value for which the relative spectral irradiance is known (*i.e.*, has been previously measured with a spectroradiometer).
(3) Measuring the reference-cell short-circuit current under such an illumination $I_{SIM}^{RC}(E_{SIM})$.

If these two operations are repeated for a set of values of E_{SIM} and the spectral response of the reference cell is known, application of Eq. (7) yields factor F_2 as a function of E_{SIM}. These operations are valid for any test cell to which the simulator may be subsequently applied, since they do not involve any information from it.

- Simulator adjustment

(4) Once the test cell has been chosen, and its relative spectral response has been measured, factor F_1 can be easily calculated as a function of E_{SIM} by using Eq. (6).

At that stage, a number of data points $F(E_{SIM})$-and, therefore, $E_{EFF}(E_{SIM})$- are available. These are valid for a given reference spectrum, simulator and test cell. In order to find out which value of E_{SIM} corresponds to a given value of E_{EFF}, a simple method can be used. The available E_{EFF} (E_{SIM}) points can be fitted to, *e.g.*, a polynomial regression from which the right E_{SIM} can be derived analytically.

Of particular importance is the fact that $E_{EFF}(E_{SIM})$ does not depend on the reference cell used (of course as long as this has been correctly calibrated in current and spectral response). This can be deduced from the following: In the evaluation of $E_{EFF}(E_{SIM})$, the reference cell is involved only through $F_2(E_{SIM})$ (Eq. (7)). If the subindex ABS is used to indicate absolute values for spectral response or simulator irradiance (please note that reference irradiance data are absolute ones from standard tables), from the definition of spectral response, the following expressions are immediate:

$$I_{SIM}^{RC}(E_{SIM}) = A^{RC} \int_0^\infty e_{ABS,SIM}(\lambda, E_{SIM}) S_{ABS}^{RC}(\lambda) d\lambda \tag{8}$$

$$I_{REF}^{RC} = A^{RC} \int_0^\infty e_{REF}(\lambda) S_{ABS}^{RC}(\lambda) d\lambda \tag{9}$$

where A^{RC} represents the reference-cell active area. The relation between relative and absolute spectral magnitudes may be written:

$$e_{SIM}(\lambda, E_{SIM}) = K_{SIM}(E_{SIM}) e_{ABS,SIM}(\lambda) \tag{10}$$

$$S^{RC}(\lambda) = K^{RC} S_{ABS}^{RC}(\lambda) \tag{11}$$

Substituting Eqs. (10) and (11) in Eqs. (8) and (9):

$$I_{SIM}^{RC}(E_{SIM}) = \frac{A^{RC}}{K^{RC} K_{SIM}(E_{SIM})} \int_0^\infty e_{SIM}(\lambda, E_{SIM}) S^{RC}(\lambda) d\lambda \tag{12}$$

$$I_{REF}^{RC} = \frac{A^{RC}}{K^{RC}} \int_0^\infty e_{REF}(\lambda) S^{RC}(\lambda) d\lambda \tag{13}$$

... and then dividing Eqs. (12) and (13):

$$\frac{I_{SIM}^{RC}(E_{SIM})}{I_{REF}^{RC}} = \frac{1}{K_{SIM}(E_{SIM})} \cdot \frac{\int_0^\infty e_{SIM}(\lambda, E_{SIM}) S^{RC}(\lambda) d\lambda}{\int_0^\infty e_{REF}(\lambda) S^{RC}(\lambda) d\lambda} \tag{14}$$

If Eqs. (14) and (7) are now compared:

$$F_2(E_{SIM}) = \frac{1}{K_{SIM}(E_{SIM})} \tag{15}$$

This means that $F_2(E_{SIM})$ is simply the inverse of the constant that relates absolute and relative simulator spectral irradiances. It does not depend on which reference cell is used. Only reliable data about this (whatever its spectral response) are needed. In other words, the reference cell is used in the calibration step just for converting relative spectral irradiances into absolute ones for a particular test-specimen position. Furthermore, the method is theoretically insensitive to the spectral distribution of the simulator light. The validity of the procedure does not depend on the similarities or dissimilarities between reference and test cell or between reference and simulated spectrum, but only on the reliability of the data used for the calculations.

Errors derived from measuring reference and test cell at temperatures different from those of STC or associated with a heterogeneous intensity distribution of light combined with differences in position and/or active area of reference and test cell are out of the scope of this work and can be addressed following the pertaining procedures included in [1].

3. EXPERIMENTAL DETAILS

The validity of the new procedure proposed has been assessed by means of a number of tests consisting of the measurement of I-V characteristics under 1 sun AM1.5G [3] global illumination from a metal-halide Steuernagel Solar Constant 575 solar simulator using:

- Two methods: the conventional [1], and the new one.
- Five photodiodes having two completely different types of spectral response.

The facility includes a Keithley 228 A electronic load, a Keithley 619 electrometer, a Schlumberger 7061 precision voltmeter, a Keithley 7402 digital thermometer, a Keithley 706 scanner and other minor elements, all of them controlled by a personal computer *via* GPIB with software developed by the authors. The short-circuit currents obtained have been compared with those derived from outdoor tests.

First of all, the relative spectral irradiances of the simulator were measured at different intensities (different values of E_{SIM}) with a spectroradiometer LI-COR model 1800 providing spectra in the range 300 – 1100 nm. Special care was taken to place the receiver well within the optical axis of the simulator and at a distance as similar as possible to the distance source-sample to be used subsequently for routine measurements.

The equations of Section 2 account for dependence on light intensity through the parameter E_{SIM}, the absolute integrated irradiance generated by the simulator on the sample plane. Since E_{SIM} is not directly known, it can be replaced in the equations by any other parameter being monotonically and reliably correlated with it. Candidates are the current intensity through the lamp, an analogue voltage control signal, the position of a control potentiometer *etc.* The simulator used in the present study is controlled by a computer, which commands light intensity by means of a single parameter, which will be called herein "control signal" (S_C), given in percent of its span (0 to 100% in S_C corresponds to 0 to maximum intensity). Having in mind the application of the equations with S_C instead of E_{SIM}, the relative spectral irradiances were measured for a given set of S_C values. Since some of the cells to be used in the study have a measurable spectral response beyond 1100 nm (roughly up to 1250 nm), the relative spectral irradiances measured had to be extrapolated to 1250 nm on the basis of typical spectra provided by the simulator manufacturer. The resulting spectral irradiances are shown in Figure 1 together with the standard one for 1 sun AM1.5G global illumination [3].

The cells used in this study, named respectively ASI1, ASI2, CSI1, CSI2 and CSI3, are crystalline-silicon single junction devices. The first two of them have a BG18 filter which modifies their spectral response imitating that of an amorphous-silicon photodiode. The spectral responses were measured by means of an optoelectronic-characterisation facility devised by the authors, consisting of a PTI monochromator, two EGG lock-in amplifiers, one EGG light chopper, two New-Focus photodetectors and a home-made current-to-voltage amplifier ensuring a less-than-0.1-Ω input impedance and a selectable gain from 10^1 to $10^8\,VA^{-1}$. The results appear in Figure 2.

The I-V characteristic of each of the cells has been measured ten times with either of the methods. This has allowed to minimise errors

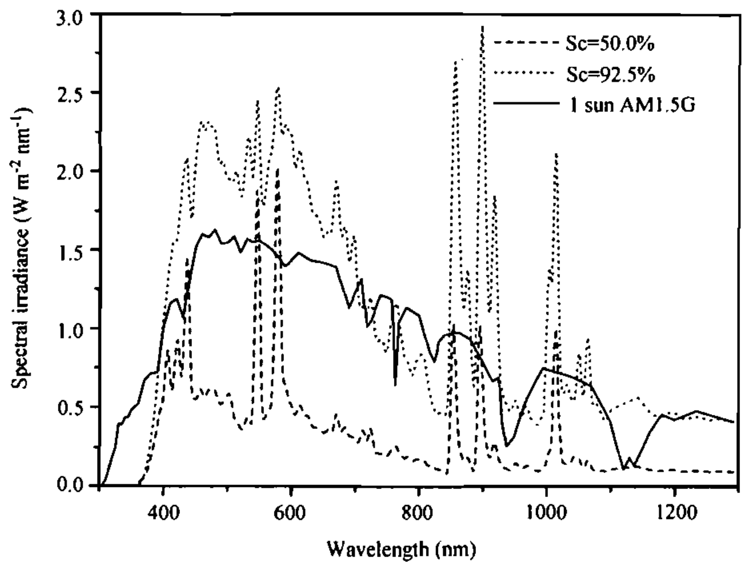

FIGURE 1 Spectral irradiances of the simulator Steuernagel Solar Constant SC 575 used, for different values of the control signal S_C as indicated. Standard 1-sun AM1.5 G global irradiance plotted for reference purposes.

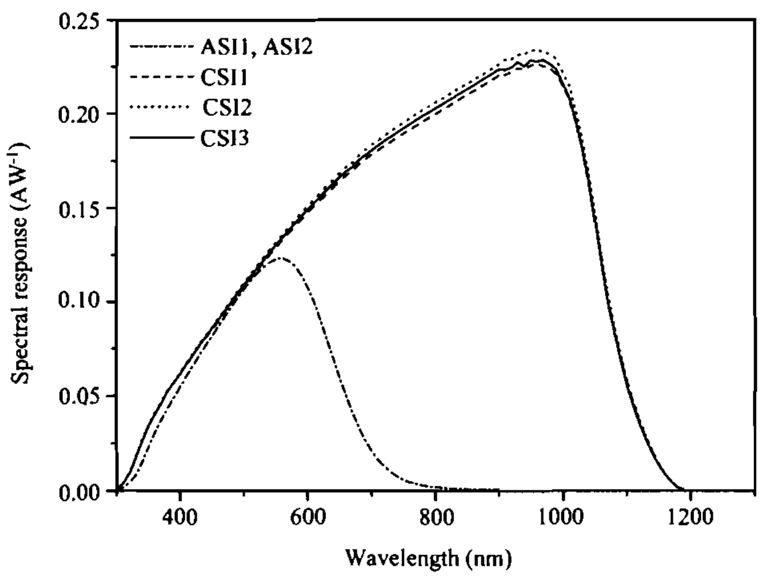

FIGURE 2 Relative spectral responses of the cells used in the present work, as measured by the authors.

from different sources and estimate their global contribution through their standard deviation. In all cases the cell identified as ASI1 (one of the amorphous-silicon-like devices) has been used as the standard for calibration. The use of such a reference for characterising not only a similar device, but also other cells having a totally different spectral response, favours the appearance of spectral-mismatch-related effects and, therefore, the assessment of the method proposed.

After a number of tests, it has become apparent that the above mentioned control signal S_C is not well enough correlated with the absolute integrated irradiance E_{SIM}, owing to stabilisation effects. Therefore a small monitoring photodiode has been installed at a certain point of the illuminated area of the simulator. An appropriate resistor ensuring short-circuit conditions has been soldered to its ends and the corresponding voltage drop, V_L, has been taken as the control parameter for the adjustment of light intensity. The equations used are, therefore, those presented in Section 2, but with V_L instead of E_{SIM}. The conventional method [1] has, thus, been applied imposing the condition that V_L should have the same value when adjusting the simulator and when measuring the test cell.

In order to get rid of temperature effects, all measurements have been done at the same temperature (40°C $\pm$ 2%). Possible errors due to irradiance nonuniformity in the measurement plane have been minimised by having cells of equal or very similar active areas and positioning them very carefully in the same point of the sample holder (which has a fix position with respect to the simulator).

4. RESULTS AND DISCUSSION

In order to illustrate the process, the effective irradiance as defined in Eq. (4) has been plotted in Figure 3 as functions of V_L, together with a polynomial fit of $F(V_L)$. The right value of V_L–which will be represented by V_L^*–corresponding to 1 sun (100 mW cm^{-2} in this case) is easily derived. The I-V curve has been measured using a feedback loop on the control signal S_C which guarantees that $V_L = V_L^* \pm 0.1\%$. At this point, it should be stressed that, once the $E_{EFF}(V_L)$ polynomial fit has been derived, not only V_L*(1 sun)*, is immediate, but also V_L for any effective irradiance wished within the range determined by the

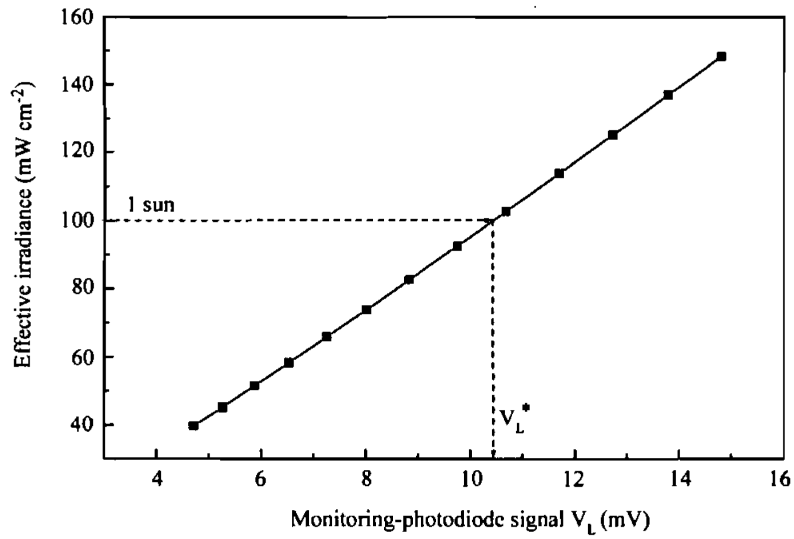

FIGURE 3 Effective irradiance as defined in Eq. (4) as a function of the light-intensity parameter V_L, which in this case is the signal of a monitoring photodiode. The plot has been obtained according to the procedure proposed by the authors, *i.e.*, by means of Eqs. (4) to (7). The polynomial fit of $E_{EFF}(V_L)$ (a straight line) is also shown, with indication of the value of V_L corresponding to 1 sun AM1.5G ($100\,mW\,cm^{-2}$).

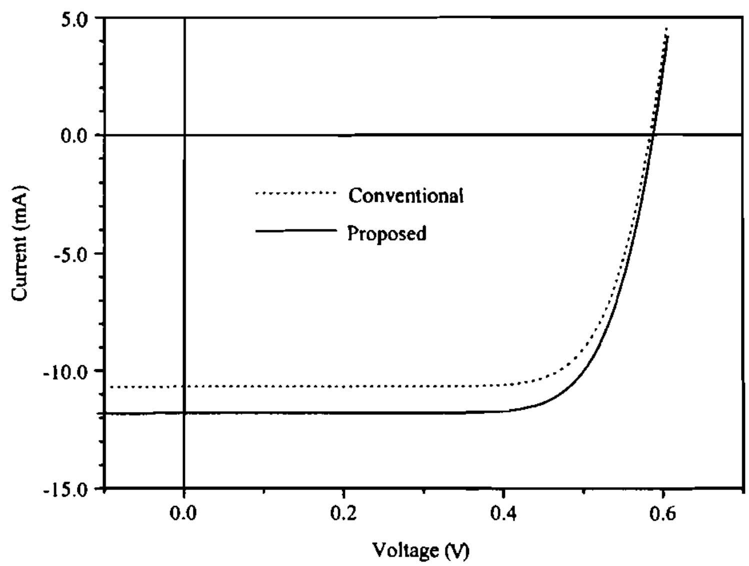

FIGURE 4 I-V characteristics of cell CSI1 under $100\,mW\,cm^{-2}$ obtained with the conventional method (without spectral-mismatch corrections) and with the authors' procedure.

TABLE I Short-circuit currents derived from the conventional method (before and after correction from spectral mismatch) and the procedure proposed (average values and standard deviations). Outdoor values indicated for error assessment. Spectral mismatch parameter corresponding to 1 sun AM1.5G global and ASI1 as the reference indicated as M

	Method									
	Outdoors		*Conventional*					*Proposed*		
Cell ID	I_{sc} *(mA)*	*Std. dev.*	$I_{sc(meas.)}$ *(mA)*	*M*	I_{sc} *(mA)*	*Std. dev.*	*Error*	I_{sc} *(mA)*	*Std. dev.*	*Error*
ASI1	4.047	0.76%	4.048	1.000	4.048	0.08%	**+0.03%**	4.050	0.49%	**+0.08%**
AS12	3.980	0.04%	4.023	0.999	4.027	0.16%	**+1.16%**	4.020	0.24%	**+0.99%**
CSI1	11.936	0.03%	10.699	0.892	11.994	0.09%	**+0.49%**	11.815	0.07%	**−1.02%**
CSI2	11.774	0.01%	10.657	0.892	11.947	0.32%	**+1.45%**	11.760	0.21%	**−0.12%**
CSI3	11.876	0.02%	10.732	0.892	12.031	0.13%	**+1.29%**	11.848	0.05%	**−0.24%**

minimum and maximum control-signal-S_C-values for which the simulator relative spectral irradiance has been measured. This feature opens a very simple way of routinely measuring I-V characteristics at different illumination levels.

Figure 4 shows the I-V curves obtained with the conventional method (before spectral mismatch corrections) and with the authors' procedure. Please note that the translation of the conventional-method curve into the spectral-mismatch-corrected ones is possible in this particular case (that of a conventional crystalline-silicon cell) on the basis of the well known one- or two-exponential models, in which the short-circuit current is strictly proportional to E_{SIM} and the curves at different irradiances are simple shifts of the dark characteristics. In the cases of devices whose currents are extracted not (or not only) by carrier diffusion, but also by appreciable (or even dominant) field-driven carrier-transport mechanisms, such as thin-film cells, the above cited curve translation is far from trivial and requires a very reliable model of current dependence on voltage in different carrier-generation conditions. Such a model, very seldom available, particularly when developing new solar-cell technologies, is unnecessary if the authors' approach is followed.

The reliability of the method can be deduced from the short-circuit currents, summarised in Table I. The key point is that the errors associated with the use of the method proposed are not higher than those involved in the conventional one. In other words, it has been demonstrated that it is possible to adjust the solar simulator irradiance before doing the I-V measurement imposing the condition that the spectral mismatch parameter be equal to unity. The outcome will be equal to that from outdoor measurements with 100 mWcm^{-2} irradiance in AM1.5 G global conditions.

5. CONCLUSIONS

A new procedure has been devised for irradiance setting in indoor I-V measurements. The method allows to use reference and test cells of different spectral responses, yields reliable I-V curves not requiring spectral-mismatch corrections and greatly facilitates testing cells of any technology, even without having any model of their $I(V)$

behaviour, under different irradiances. The errors of the tests performed lie well within the ranges defined by the procedures previously established.

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