Solar cell characterization

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I. Introduction

The solar cell characterizations covered in this chapter address the electrical power generating capabilities of the cell. Some of these covered characteristics pertain to the workings within the cell structure (e.g., charge carrier lifetimes) while the majority of the highlighted characteristics help establish the macro performance of the finished solar cell (e.g., spectral response, maximum power output). Specific performance characteristics of solar cells are summarized, while the method(s) and equipment used for measuring these characteristics are emphasized.

The most obvious use for solar cells is to serve as the primary building block for creating a solar module. As such, a key pursuit is to manufacture a solar module, or more correctly, to manufacture each unique model or product line of photovoltaic (PV) module, using cells that perform as similarly as possible. To achieve that end, manufacturers conduct quick measurements of mass-produced cells and then allocate them into a few groups or "bins" based on those measurements. The key cell characteristic(s) used for binning are embodied in the cell's electrical current versus voltage (*I-V*) relationship, Fig. 1. From these curves, the cell's maximum power output, short circuit current, and open-circuit voltage, in particular, are identified.

Additional cell parameters and relationships are used to more fully characterize a solar cell. These additional characteristics include, but are not limited to, spectral response, fill factor, series resistance, temperature coefficients, and quantum efficiency. Knowledge of these additional parameters is helpful, for example, when developing, evaluating and fine tuning a new cell design and manufacturing

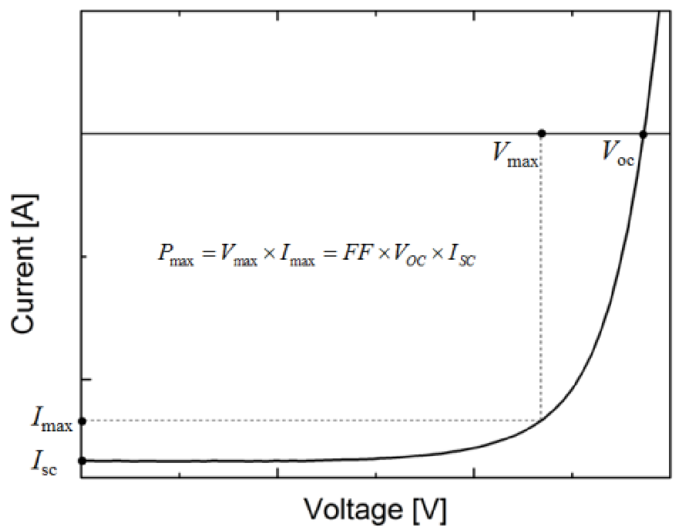

Fig1. A generic *I-V* curve of a solar cell under sun illumination.

process. Characterizations that focus on maximizing accuracy, moreover, are especially important for the purpose of creating reference cells. Reference cells serve as transfer standards that can be used by manufacturers and 3rd party testing laboratories to generate and verify, respectively, published ratings of production cells and modules. Most primary PV characterization laboratories aim to achieve overall uncertainties of better than 1 % on their standard reference cells, while the secondary labs aim to achieve better than 2 % overall uncertainties when calibrating cells for customers.

II. *I-V* Curves: Features and Uses

Measurements of the electrical current versus voltage (*I-V*) curves of a solar cell or module provide a wealth of information. Solar cell parameters gained from every *I-V* curve include the short circuit current, I_{sc}, the open circuit voltage, V_{oc}, the current I_{max} and voltage V_{max} at the maximum power point P_{max}, the fill factor (*FF)*, and the power conversion efficiency of the cell, η [2–6]. These parameters are shown in the Fig. 1 *I-V* curve for a generic single-junction cell when subjected to a specific level of solar illumination and otherwise operated at a specific set of conditions. Notably, the *FF* is an indication of internal losses that is visually communicated by how much the *I-V* characteristic curve deviates from a rectangular shape in the shown 4th current-voltage quadrant.

The electrical generation of a photovoltaic cell (or module), as revealed in its *I-V* curves, depends on many factors, including, but not limited to, the incident solar radiation spectrum, the orientation of the cell relative to the beam component of that solar input, the resulting operating temperature of the cell, and the applied electrical load that completes the DC circuit. To readily allow comparisons between cells, *I-V* curves are measured and reported based on common sets of operating conditions. The primary set of operating conditions is the Standard Reporting Conditions (SRC), which are also called Standard Test Conditions (STC). The standard reference spectrum for SRC is an air mass 1.5 global (AM 1.5G) solar spectrum with a total irradiance of 1000 W/m^2 [1]. This spectrum corresponds to what would typically be observed at the surface of the earth for mid-latitudes. The SRC specified device operating temperature is 25 ºC. Finally, when the power rating of a cell or module is reported and used to market the product, it almost always corresponds to the current-voltage pair along the SRC *I-V* curve that yields the highest power.

From a practical point of view, it is difficult to obtain SRC conditions in an outdoor setting. Therefore, most testing laboratories perform these electrical measurements under simulated sunlight in an indoor environment. Indoor testing under a solar simulator has several advantages over outdoor measurements; indoor testing, however, also introduces some measurement challenges, as discussed below.

Solar simulator *I-V* curve measurements of cells are typically carried out in the testing laboratory by employing a second cell, a calibrated reference cell. This reference cell is used to monitor and measure the total irradiance of the solar simulator during *I-V* testing. Based on this measurement, the output of the solar simulator can be adjusted to provide the approximate intensity required (e.g., 1000 W/m^2 for SRC) and to normalize the output from the device under test to this nominal rating condition. A commonly used reference cell is a Si cell packaged based on the World Photovoltaic Scale (WPVS) design[7]. Reference cells can be purchased directly from commercial vendors or, in some cases, obtained directly from a certified secondary laboratory. Vendors, who package the reference cells but lack in-house calibration capabilities, will have the cell calibrated by the certified secondary laboratory or, in some cases, by a primary calibration laboratory such as the National Renewable Energy Laboratory in the USA.

If the reference cell has very similar characteristics (e.g., spectral response) to the cell under test, then *I-V* testing is relatively straightforward. However, that scenario is not often the case, such as when one is trying to measure the *I-V* curve of a CdTe solar cell and the only available reference cell is Si-based. In such cases, a deviation arises from the *mismatch* between the responsivity of the two cells. For example, the reference cell may indicate an irradiance of 1000 W/m^2 even if the spectrum deviates from the nominal AM 1.5 spectrum. If the device under test is not responsive in the part of the simulator's spectrum that deviates from AM 1.5, a scaling to 1000 W/m^2 will not be representative of the test cell's actual performance under AM 1.5. Furthermore, since the majority, if not all, of the solar simulators do not generate a true irradiance match to the sun or may not have the same level of light collimation as the sun, an additional source of error is introduced into the electrical measurements. The resulting adverse impact on the *I-V* measurement may become significant with second and third generation PV cell technologies when the operator primarily uses a single crystalline silicon cell as the reference cell. Fortunately, there is a way to compensate for these deviations, by calculating a spectral mismatch factor, *M*, and using it to correct each electrical current value from the raw *I-V* curve data[3]. Furthermore, the temporal stability of the light source during the course of the measurement and the uniformity of the illumination at the measurement plane can also introduce errors. Key steps for determining a mismatch factor, along with other useful information that aids in performing successful *I-V* measurements of single-junction solar cells and modules, are described in the below chapter subsections.

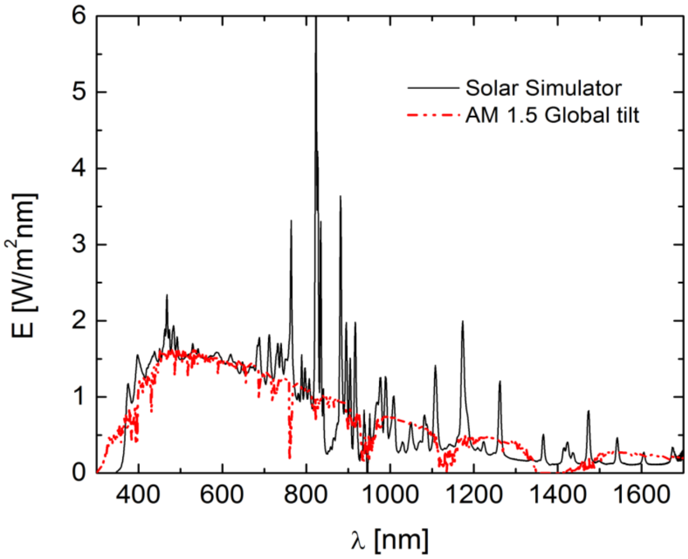

Fig. 2. The irradiance spectrum of a Xe flash solar simulator. For comparison, the AM 1.5 G spectrum is also plotted.

III. Solar simulator performance

A solar simulator is a light source with a broad band optical output similar to that of the sun over the response range of different solar cell technologies. Solar simulators can be used for electrical characterization of solar cells as well as irradiance exposure of materials and devices. A solar simulator operates in either a steady-state mode or a pulsed mode. The type of lamp used in the simulator can vary among different models. Xenon arc lamps, metal halide arc lamps, quartz tungsten halogen lamps, and light emitting diodes have all been used in simulators, with Xe lamps being the most common[4]. Regardless of the type, a solar simulator is currently [8] evaluated based on three unique criteria: 1. Spectral match to the reference spectrum over a certain wavelength range, 2. Non-uniformity of the irradiance within the measurement test plane, and 3. Temporal instability of the irradiance during the course of the measurement. Irradiance represents the power of the electromagnetic radiation per unit area of the incident surface and is expressed in units of watts per meter squared (W/m^2). When the irradiance measurement is expressed as a function of the wavelength, it is called *spectral irradiance* and has units of W/m^3, or more commonly, $W.m^{-2}.nm^{-1}$.

Fig. 2 shows the irradiance spectrum of a Xe flash solar simulator compared to the industry standard AM 1.5 global tilt spectrum. Although the Xe simulator provides a reasonably good match to the sun spectrum, the match is not without substantial deviations, particularly at wavelengths greater than 800 nm. As per the current IEC standard for evaluating a solar simulator [8], the radiant energy delivered at the test plane by the simulator for 6 contiguous wavelength intervals is first determined. The irradiance for each interval is then divided by the total 6-interval irradiance and the resulting 6 percentages are compared with the percentages for the reference spectrum. This comparison is achieved by calculating the ratio of the percentage from the simulator to the corresponding percentage for the reference spectrum. A letter grade is assigned for each wavelength interval based on the magnitude of the ratio relative to limits prescribed in the consensus standard. For example, a ratio between 0.75 and 1.25 constitutes an “A” rating while a “B” rating is assigned if the ratio falls outside the A range but within 0.6 and 1.4. The overall spectral grade of the solar simulator is assigned based on the lowest grade for any interval. Thus, for a simulator to achieve a Class A rating with respect to spectrum, a ratio between 0.75 and 1.25 must be achieved for all 6 intervals. This calculation is demonstrated for the simulator data of Fig. 2 in Table 1. This simulator obtains a rating of A for spectral match although it can be seen that the 800 nm to 900 nm interval is on the A/B class borderline (1.25).

Wavelength range [nm]	Measured percentages	IEC Standard percentages	IEC ratio	Class rating
400-500	18.8 %	18.4 %	1.02	A
500-600	18.3 %	19.9 %	0.92	A

600-700	16.9 %	18.4 %	0.92	A
700-800	16.9 %	14.9 %	1.13	A
800-900	15.4 %	12.5 %	1.24	A
900-1100	13.7 %	15.9 %	0.86	A

Table 1: Example of the spectral mismatch rating determination for the Xe solar simulator described above.

Regarding the nonuniformity of irradiance, a rating of A is given to a simulator with better than 2 % for its “Non-uniformity of irradiance percentage” as calculated below. The limit for a class B rating is 5 % while the limit for a class C rating is 10 %. The non-uniformity is evaluated by dividing up the test area into at least 64 equal blocks and using a detector to measure irradiance. A broadband detector having the needed small footprint, while being stable, sufficiently fast, and having a linear response over the range of the measured irradiances is recommended. If the temporal stability of the light source is questionable over the course of completing the set of irradiance measurements, then the measurements should be performed all at one time using an array of calibrated detectors. The non-uniformity is obtained from the relation:

$$\text{Non-uniformity}(\%) = \left[\frac{\max irradiance - \min irradiance}{\max irradiance + \min irradiance}\right] \times 100 \quad (1)$$

where max and min correspond to the maximum and minimum irradiance levels across the measured test plane.

The temporal instability of the simulator must also be evaluated and involves

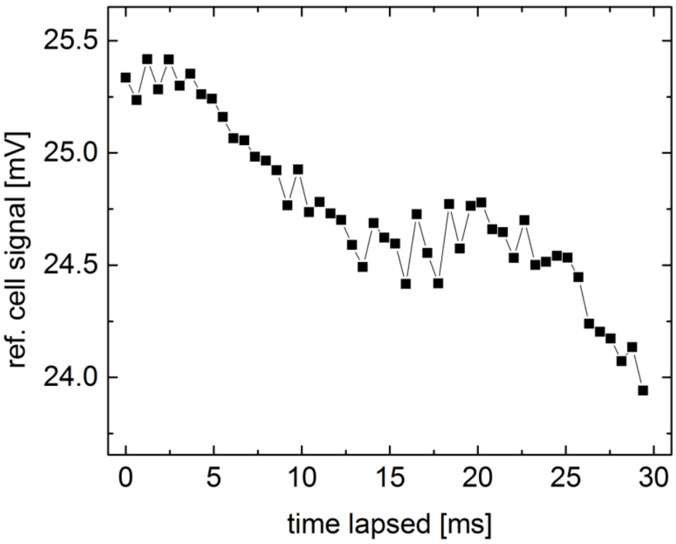

Fig. 3. The temporal stability of a flash solar simulator during the course of a 30 ms *I-V* measurement.

both short term instability and long term instability. Short term instability is evaluated over the sampling interval of each unique data set (voltage, current, irradiance) during the *I-V* measurement whereas long term instability considers the variation in the simulator's generated irradiance over the entire *I-V* curve measurement. Interestingly, long term temporal instability is calculated using the exact same equation as given above for non-uniformity – only now using data collected during the actual *I-V* curve measurement – with the grading limits also being the same (i.e., 2% for A, 5% for B, and 10% for C). Fig. 3 shows an example of long term temporal instability monitoring for a flash solar simulator during a 30 ms time interval when an entire *I-V* sweep was performed (with a total flash duration of 36 ms). These data reveal a temporal instability of just under 3 %, for a B rating. In cases such as this, normalizing each *I-V* data pair to the average measured irradiance by using the corresponding irradiance measurement is recommended in order to reduce the uncertainty in the final curve. Alternatively, other actions (such as changing the light bulb, servicing the power supply electronics, etc.) can be pursued in an effort to minimize the issue. Otherwise, one must accept the larger uncertainty associated with the *I-V* measurement.

IV. Spectral irradiance measurements

The spectral output of a solar simulator or any light source is measured using a calibrated spectroradiometer[9, 10]. Nowadays, these instruments are typically spectrographs equipped with fast photodiode arrays or Si charge-coupled devices (CCD) that provide sensitive and reliable information regarding the spectrum and intensity of the light. In order to obtain a sufficiently wide spectral range, two or more types of detector arrays might be necessary, such as Si- and InGaAs-based arrays. Furthermore, correct measurements of irradiance require the spectroradiometer to be calibrated against a known light source such as a calibrated 1000 W FEL lamp[9]. An FEL lamp is an ANSI standard 1000 W tungsten halogen incandescent lamp, and its calibration is based on the absolute radiometric determination of the freezing temperature of gold. The calibrated reference lamp needs to be operated under a set of very precise conditions. The most important of these operational conditions are: (1) the use of a very stable, high accuracy power supply with a feedback mechanism for precise control of the lamp's current (typically 8.2 A) and (2) the proper alignment and placement of the spectroradiometer collection optics at a specified distance from the center of the bulb filament. Since an output accuracy of better than 0.1 % is typically required, the lamp's input current has to be set and maintained to better than 0.01 % during the course of the calibration.

Periodic calibration of the spectroradiometer is necessary to ensure an overall low uncertainty budget. Additionally, the irradiance characteristics of the simulator must be measured on a regular basis because, as the lamps age, the shape of their spectral output changes as well. A change in the shape of the spectrum not only can affect the overall class rating of the solar simulator but also can significantly impact the corrected *I-V* curve, as elaborated later in this chapter.

V. Spectral response measurements of solar cells

The spectral responsivity of a solar cell, R, – which quantifies the wavelength dependence of the cell's photocurrent generation when normalized for the input irradiance or the radiant power of the incident monochromatic radiation – is a very informative and thus useful photovoltaic characteristic[11–18]. Cell spectral responsivity (SR), for example, is used to calculate quantum efficiency, which indicates the cell's conversion efficiency as a function of wavelength. The absolute determination of the SR of a solar cell, if done under appropriate conditions such as uniform overfill illumination and proper light biasing, can be used to predict the short circuit current, I_{sc}, of the test device under any incident spectral irradiance, including the standard AM 1.5 solar spectrum[11]. One advantage of this absolute SR approach is that it provides a direct route for SI traceability of the I_{sc} measurement via a cryogenic electrical substitution radiometer, a route that differs from the more common approach of having traceability to the World Radiometric Reference (WRR) scale. Another leading use of relative (or absolute) SR data of PV

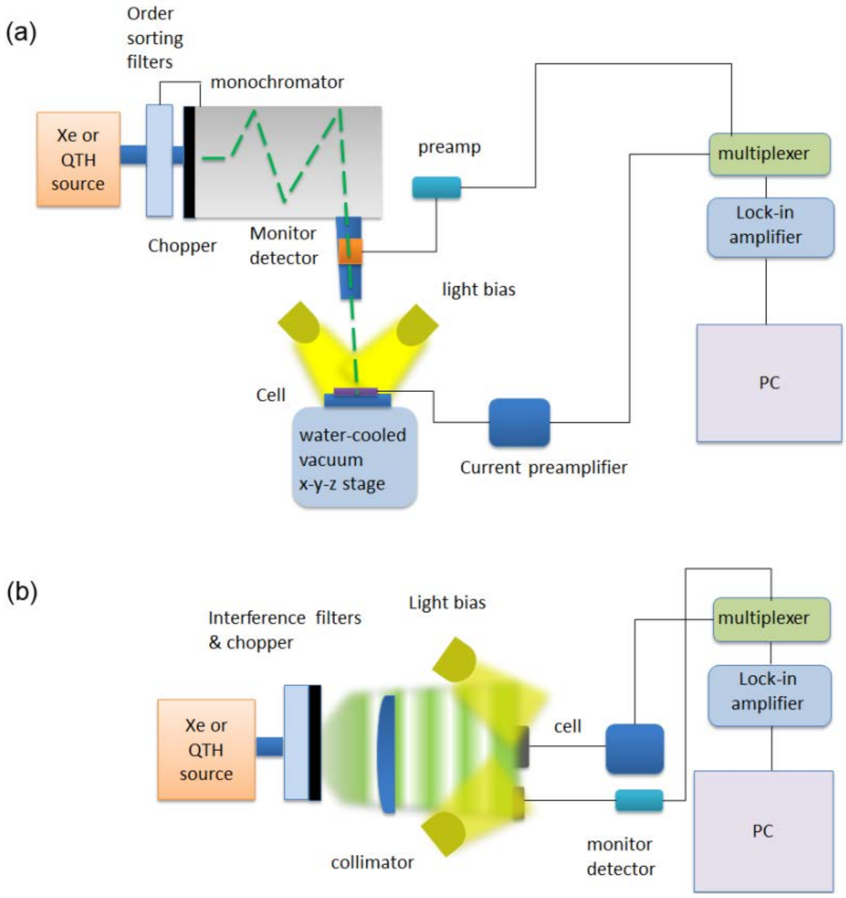

Fig 4. (a) Schematics of a monochromator-based SR measurement system where the probe beam underfills the cell. (b) An example of an SR measurement system where the beam overfills the cell.

cells is to adjust *I-V* data to account for spectral differences between spectrum of the actual illumination source versus the chosen reference. Finally, SR curves can be used in modeling and simulations to provide important physical quantities such as the charge carrier diffusion length or for studying bandgap defect densities within the active layer of the device[19]. These physical parameters are an important indication of the quality of the semiconductor material comprising the active layer.

The differential spectral responsivity (DSR) method is the most widely used method for measuring the SR of a solar cell. Using this technique, a small modulated (quasi) monochromatic light beam and a more intense steady-state white light source (the light bias) simultaneously illuminate the solar cell, producing a photocurrent that is the sum of these two sources: a small pulsed signal superimposed on a larger steady current. The pulsed signal is separated, amplified and detected using a lock-in amplifier that is synced with the user-selected modulation rate of the chopped monochromatic beam. A small portion of the monochromatic beam is diverted towards a monitor photodetector in order to measure the beam's radiant power. This radiant power, which is recorded by the same or by a separate lock-in amplifier, coupled with the cell's pulsed current and the monochromator's known passed wavelength, collectively define each discrete SR data point. The set of these discrete points, in turn, is used to construct the overall SR curve. As for the radiant power of the bias light and the resulting steady dc current of the cell, the impact on the SR measurement has been described previously, particularly for certain types of solar cells[14, 15, 20].

The spectral response measurements of a PV device can be performed in either the power-mode or the irradiance-mode, and each measurement can be either a relative or an absolute measurement. Power-mode measurements require the knowledge of the monochromatic beam's radiant power, typically obtained using a calibrated, SI-traceable reference photodetector. For power-mode, the monochromatic beam is sized such that it illuminates only part of the reference photode-

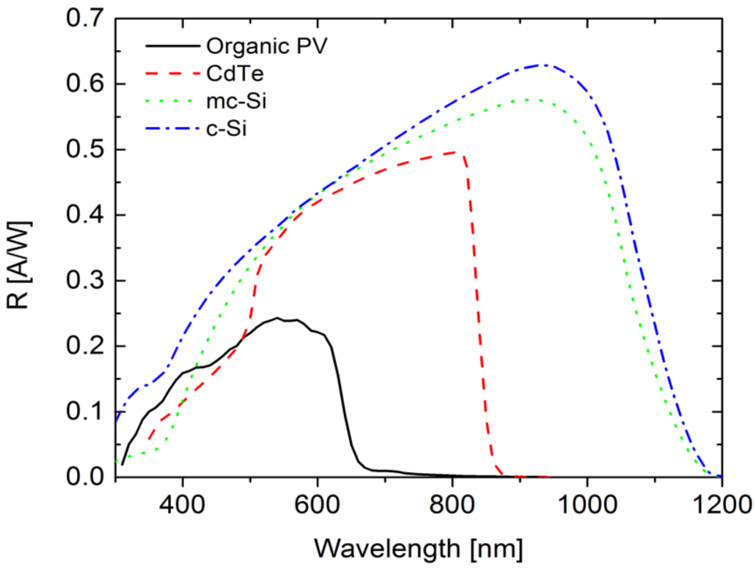

Fig. 5. Power mode spectral response curves of a few different types of solar cells.

tector and then only a smaller part of the test cell (i.e., underfilling). For the irradiance-mode, the irradiance or incident power per unit area of the monochromatic beam is required. Irradiance can be determined by fully illuminating (i.e., overfilling) a very spatially-uniform reference photodetector with the incident monochromatic radiation and then dividing the measured beam power by the aperture area of the detector. The incident beam should have a very spatially uniform irradiance profile. The absolute SR in power-mode has SI units of A W^{-1}, whereas the absolute SR in irradiance-mode is reported in units of A m^2 W^{-1}.

Fig. 4(a) shows a schematic of a simple monochromator-based SR measurement system designed to measure the spectral response data in the power- mode. A mechanical chopper placed within the light path of the monochromator causes the excitation light to be in the form of a square wave, generating a pulsed signal in the device under test. The cell is simultaneously illuminated with a set of bias lights operated in a steady dc mode. The pulsed signals from both the cell and the monitor photodiode are measured by a lock-in amplifier sequentially for each wavelength. The spectral response data can be constructed from these individual measurements. Fig. 4(b) shows the design of a system where the entire cell area is uniformly illuminated by the monochromatic beam. If the irradiance of this beam is measured using a calibrated reference detector, then the irradiance mode SR data can be obtained using this setup. To achieve an overfilling monochromatic beam, interference filters can be used to narrow down the broadband beam into a quasi-monochromatic one; afterwards, an optical lens assembly can be used to project this light on to the test cells. Other types of light sources such as light emitting diodes (LEDs) and lasers can also be used as monochromatic sources [21–23]. With respect to these two measurement options, the more accurate and viable route for obtaining the I_{sc} of a solar cell is achieved using the irradiance

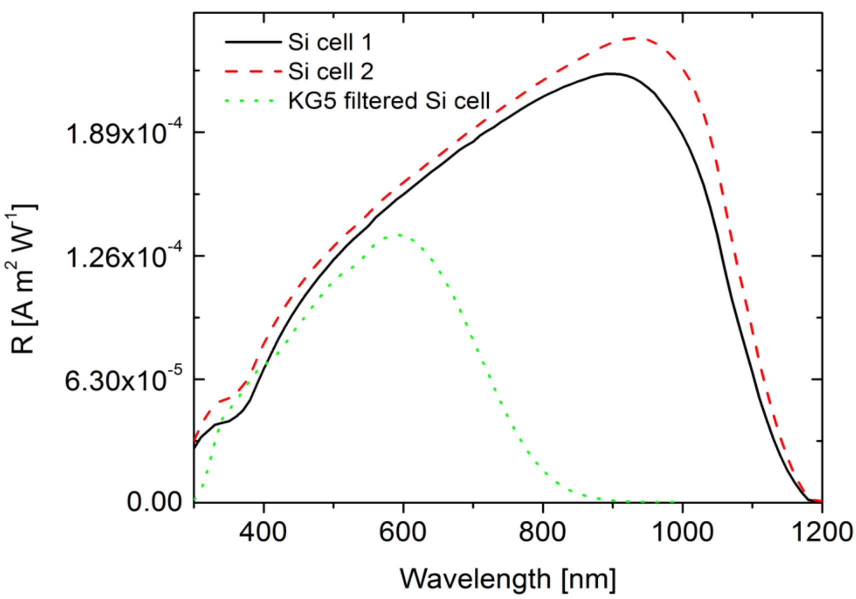

Fig. 6. Irradiance mode spectral response curves of a few solar cells.

mode SR curve of the cell. The lack of spatial material uniformity across the cell and/or the presence of metal fingers on the front surface of the cell can lead to variances in the cell's overall spectral response if measured using the underfilled power responsivity measurements. These particular complications are avoided when using the overfilled irradiance responsivity measurements; the impacts of such cell features are accounted for in the method because the test setup is consistent with the eventual overfill deployment in a solar simulator or outside in the sun.

Fig. 5 shows the spectral response curves of a few different types of single-junction solar cells, obtained in power-mode. As shown, the spectral response can vary significantly among different photovoltaic materials. The higher wavelength cutoff is directly related to the bandgap of the absorber layer. Also, the actual magnitude of each curve is directly proportional to the total photocurrent generation under illumination. For the purpose of evaluating the mismatch factor *M* (discussed in the next section), relative SR curves (normalized to 1) or absolute SR curves in power-mode such as those plotted here are generally sufficient, as long as the local spatial variations of SR do not cause the overall shape of the curve to change. If there is a significant change in the shape of the curve when the probe beam is moved across the surface of the cell, then either an averaging algorithm must be applied to estimate the correct shape or the SR must be reevaluated in the irradiance (overfill) mode.

Fig. 6 shows the irradiance-mode SR data for three solar cells. From these data, the I_{sc} of the cells subjected to AM 1.5 global tilt spectrum can be directly calculated, provided the spectral response, *R*, is measured under short circuit conditions:

$$I_{\mathrm{sc}} = \int R_{\mathrm{irrd\ mode}}(\lambda)\ .\ E_{\mathrm{AM1.5}}(\lambda)\ d\lambda \tag{2}$$

where $E_{\mathrm{AM1.5}}(\lambda)$ is the spectral irradiance associated with AM 1.5 global tilt conditions.

VI. Spectral mismatch factor

The spectral mismatch factor, *M*, corrects for: 1) the mismatch between the spectral response of the PV test cell and the PV reference cell, and 2) the mismatch between the illumination source and the reference spectrum (e.g., AM 1.5G). This correction factor is evaluated using:

$$M = \frac{\int_{\lambda 1}^{\lambda 2} E_s(\lambda) R_t(\lambda) d\lambda}{\int_{\lambda 3}^{\lambda 4} E_s(\lambda) R_r(\lambda) d\lambda} \times \frac{\int_{\lambda 3}^{\lambda 4} E_r(\lambda) R_r(\lambda) d\lambda}{\int_{\lambda 1}^{\lambda 2} E_r(\lambda) R_t(\lambda) d\lambda} \tag{3}$$

where $E_s(\lambda)$ is the spectral irradiance of the source, $E_r(\lambda)$ is the reference spectral irradiance, $R_t(\lambda)$ is the spectral response of the test cell, and $R_r(\lambda)$ is the spectral response of the reference cell [3]. The integrals should be evaluated over the full range of the device's responsivity. Additionally, it is noted that only relative irradiance and responsivity data are required to perform this calculation as multiplicative factors in the numerator and denominator cancel out. This relative option is a particularly favorable aspect of this calculation because maintaining the absolute scale is a major challenge for most secondary laboratories, especially with regard to the irradiance measurements.

Prior to reporting or using any type of *I-V* test curve, the mismatch factor associated with the test setup must be calculated and applied. Table 2 shows a few examples of this calculation for various combinations of test cells, reference cells and simulator sources. Notably, even nominal mono-crystalline Si cells have sufficiently different spectral response curves among each other so that *M* will not be exactly 1. For example, the calculation provided in row 1 shows *M* = 1.007, which can cause a 0.7 % error in current measurements during *I-V* testing if not taken into account. Among typical solar simulators, such as a Xe flash-based simulator and a Xe steady state simulator, noteworthy differences can result. For example, a CdTe solar cell measured under a Xe flash simulator yields a *M* = 1.03, while under a steady state Xe simulator *M* = 1.10. These differences, which originate from differences in the irradiance spectrum, may not necessarily be due to the Xe source itself but rather related to the filters that manufacturers design and install in front of the light source to make them better match to the sun's spectrum. The calculations with the organic PV cell under various combinations are also revealing.

Cell Type	**Reference Cell**	**Simulator type**	***M* factor**
m-Si	m-Si	Xe Flash	1.00685
CIGS	m-Si	Xe Flash	0.998028
CdTe	m-Si	Xe Flash	1.03383
CdTe	m-Si	Xe steady state	1.10333
OPV	m-Si	Xe Flash	0.975193
OPV	m-Si	Xe steady state	1.15999
OPV	KG5 filtered Si	Xe steady state	1.00692
OPV	m-Si	White LED	2.1222
OPV	KG5 filtered Si	White LED	1.1377

Table 2: Examples of spectral mismatch factor calculations for different combinations of solar cells, references and solar simulator sources.

The third OPV calculation, for instance, shows that if the reference cell used is a KG5-filtered Si cell instead of a regular Si cell, the mismatch error will only be 0.7 %, as compared to the 16 % for the combination of the Xe simulator and a m-Si reference cell. Finally, if a white LED light source is used as the solar simulator, then the error in *I-V* measurements with an OPV test cell and a m-Si reference

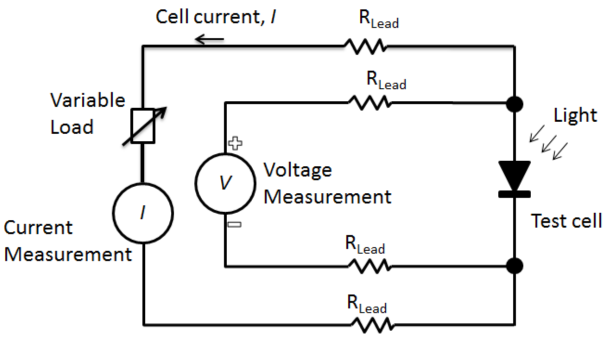

Fig 7. 4 wire *I-V* measurement schematic

cell exceeds a factor of 2. Here again, the error can be substantially reduced (to *M*= 1.14) if the reference m-Si cell was replaced by a KG5 filtered Si cell.

VII. Measuring *I-V* Curves

The correct setup for performing *I-V* measurements on a solar cell is based on a 4-wire connection (also known as Kelvin configuration) as depicted in Fig. 7. These connections are sometimes referred to as source leads and sense leads [24]. The current flows through the source leads and the device under test, and the voltage across the device is measured by sense leads. Since the input impedance of the sense leads are very high, the source current will not flow through the sense leads and therefore only the voltage across the device is measured. By comparison, if a simple 2-wire connection were used to take the *I-V* data, the current flowing through the leads will cause a voltage drop in the leads in addition to the potential drop across the device; hence, the voltage measurement across the circuit will not be that of the voltage across the cell. This effect can be particularly significant for larger area solar cells where a large photocurrent is generated in the cell under SRC or comparable illumination. With this large current, the voltage drop due to lead resistance will be more significant, hence pointedly altering the shape of the *I-V* curve.

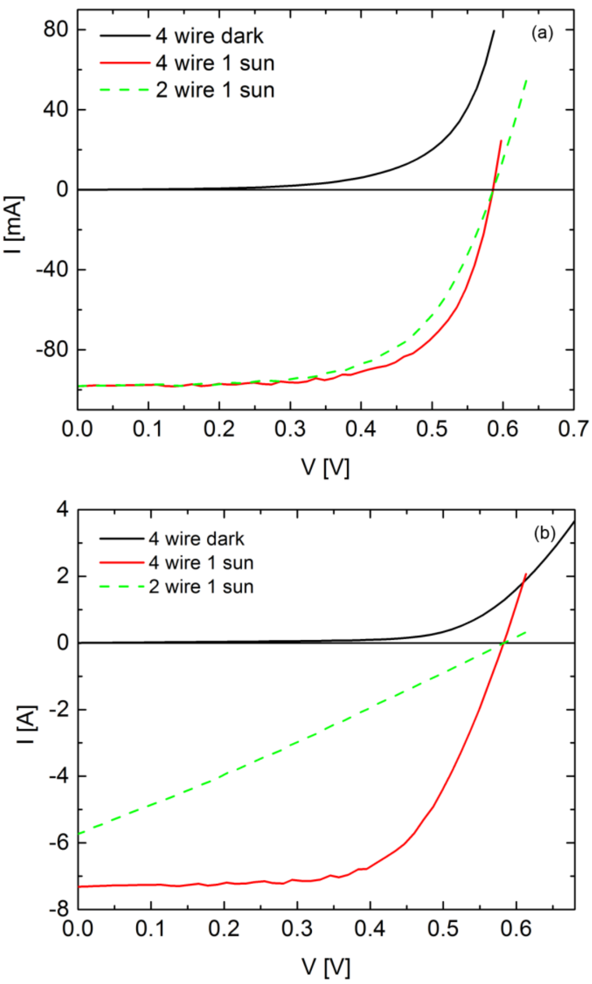

Fig. 8. (a) Comparison between 2 wire and 4 wire *I-V* measurements on a small 4 cm^2 solar cell. (b) Same comparison on a larger cell with an area of 219 cm^2. The *I-V* curves measured in the dark are also plotted for both solar cells.

Fig. 8a shows the 4-wire vs. 2-wire *I-V* curve data for a 2 cm by 2 cm Si solar cell under 1-sun illumination intensity. For this measurement, the parameter more noticeably affected by the 2-wire measurement is the *FF*, showing a slight reduction. This reduction impacts the measured power conversion efficiency of the device, although the I_{sc} and the V_{oc} are relatively unaffected. In Fig. 8b, the 2- and 4-wire *I-V* curves for a copper indium gallium diselenide (CIGS) cell with an area of ≈ 219 cm^2 are shown under illumination. The series resistance-inflicted potential drop is so significant that the entire shape of the *I-V* curve is altered (dashed line), leading to a completely unsatisfactory and inaccurate measurement. These results illustrate the importance of performing 4-wire *I-V* measurements on solar cells, particularly for large area cells or on cells with relatively low internal series resistance. It is noted that if the device itself presents a large series resistance to current flow (such as by having poor contacts), then the effect of the circuit resistance on the *I-V* curve might be less pronounced. Only in cases like this, the use of 2-wire measurements may be acceptable.

Prior to obtaining solar cell *I-V* measurements, the series resistance R_s of the cell must be determined unless the total irradiance is expected to be within ± 2 % of the SRC [5]. Additionally, the cell temperature must be measured to be within ± 1ºC of the SRC conditions. The reference cell temperature must also be measured, and a correction must be applied to its output if it is different from the temperature of the standard reporting conditions. This correction would require knowledge of the temperature coefficient of the reference cell. Under the simplified assumptions that the operating temperature is at the standard reference temperature and the total irradiance is very near the standard reporting irradiance, E_0, (i.e., 1000 Wm^{-2}), each *I-V* data point measured under the illumination source should be corrected by:

$$I_0 = \frac{I.E_0.C}{M.I_r} \tag{4}$$

$$V_0 = V - R_s(I_0 - I) \tag{5}$$

where $C = I_{sc,r} / E_0$ is the calibration constant of the reference cell, $I_{sc,r}$ is the short circuit current of the reference cell measured under SRC by a primary or certified laboratory, I_r is the monitored current of the reference cell during the course of the measurement, and I_0 and V_0 are the corrected current and voltage measurements for reporting under the SRC. I_r must be monitored for each *I-V* data pair if the long-term temporal instability of the light source is greater than 0.1 %. R_s determination is not needed if the measured total irradiance remains to within ± 2 % of the standard reporting total irradiance [5]. It can be seen that the parameter *M* plays an important role in the correct evaluation of the *I-V* curve as described earlier.

From the full set of corrected I_0-V_0 data, the four parameters I_{sc}, V_{oc}, V_{max} and I_{max} are extracted. The fill factor, *FF*, is given by:

$$FF = \frac{I_{max} V_{max}}{I_{sc} V_{oc}} \tag{6}$$

and the power conversion efficiency, η, is determined from:

$$\eta\ [\%] = 100 \frac{(I_{sc} / A) V_{oc} FF}{E_0} \tag{7}$$

where A is the cell total frontal area including contacts, and E_0 = 1000 W m^{-2} for AM 1.5G illumination conditions.

Fig. 9 shows the *I-V* curve for a small solar cell both before and after correction by equation 3 (without V_0 correction). These data were recorded under a solar simulator with temporal stability as shown in Fig. 3. Since the total irradiance lev-

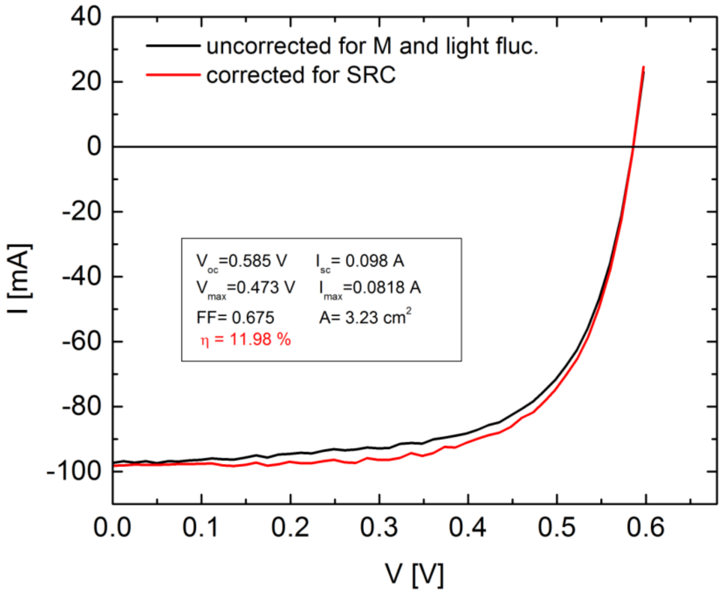

Fig. 9. (a) I-V curves for a solar cell before and after correction of the raw measurement to standard reporting conditions. The reason for the noise in the data is related to the short term fluctuations in the lamp's intensity profile.

els changed during the course of the measurement, the correction of the measured current by Eq. 3 was necessary for every data point in order to obtain the correct form of the *I-V* curve. Additional device parameters and the calculated power conversion efficiency under AM 1.5 G conditions are shown next to the plot.

VIII. Additional remarks

The aim of the various sections outlined in this chapter is to present a clear and coherent picture for performance measurements and characterization of solar cells. The presented list of challenges and requirements is by no means comprehensive and there are various other issues in addition to those mentioned previously that can complicate the measurement process. For example, recent measurements by the author and by other groups have revealed that the degree of light collimation from the solar simulator incident upon the test and the reference cell specimen may influence the spectral response and the *I-V* measurement results [25]. This effect has been found to originate from the differences in the angular response (cosine response) of the two cells. Overall, the more collimated the light source is, the lower the error associated with this angular mismatch. Ideally, primary reference cells are calibrated either outdoors or when subject to conditions similar to the level of collimation achieved from the sun (88 % direct incidence for the AM 1.5 global reference).

Finally, the light-level correction errors which were addressed by Eqs. 4 and 5 in the previous section, become more significant if the *I-V* measurement are performed substantially below or above (> ±5 %) the standard irradiance (i.e., 1000 W m^{-2}). In such case, additional corrections are recommended [26]. In general, all the uncertainties affecting the various aspects of the measurement should be considered and reported with the performance parameters.

IX. Summary

A detailed review of the various steps and requirements needed to achieve accurate photovoltaic performance measurements was presented. Characteristics of the indoor solar simulator have been presented and the steps needed to verify the class rating of the simulator were discussed in detail. Solar simulators should provide for a uniformly illuminated test plane that qualifies as Class A. Additionally, the irradiance spectrum of the simulator must be measured and compared with the standard reference spectrum. For cases where the reference solar cell has a different spectral response behavior than the test cell, a parameter called the spectral mismatch factor needs to be calculated based on the measurements of the irradiance and the spectral response of both the reference and the test cells. The irradiance and the spectral response measurement systems should be calibrated against light sources of known irradiance and reference photodiodes with known spectral response. The current vs. voltage (*I-V*) measurements must be performed in four-wire configuration and ideally at total irradiance levels near the standard reference conditions. The light source temporal stability must also be monitored during these measurements and a correction applied to the collected data if the source is not perfectly stable. The objective of most primary and secondary certification laboratories is to maintain a total relative uncertainty of less than 1 % for smaller-sized cells and 2 % for cells up to 15 cm in size. Other testing laboratories should aim for uncertainties of generally less than 5 % within a 95 % confidence interval.

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