METHODS FOR MEASURING SOLAR CELL EFFICIENCY INDEPENDENT OF REFERENCE CELL OR LIGHT SOURCE

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ABSTRACT

The accurate measurement of the photovoltaic conversion efficiency under standard test conditions is essential for meaningful comparisons of the device performance of different types of solar cells. A methodology is presented for calibrating reference cells and calculating spectral mismatch factors, and then using these to obtain the corrected short-circuit current with respect to standard test conditions. Using this technique, the current, and hence efficiency, of a given photovoltaic device can be measured with an accuracy of better than 2%, independent of the spectral response of the reference cell or the spectral irradiance of the light source. A second method does not use a reference cell, but depends on an absolute spectral irradiance measurement, and has an accuracy of approximately 5%. Both of these techniques for obtaining corrected short-circuit current are preferred over other less accurate methods.

INTRODUCTION

The efficiency of a photovoltaic (PV) device should be measured with respect to a set of standard test conditions which are defined by a temperature, area, intensity, and spectrum. The limiting uncertainty in solar cell efficiency measurements is the measurement of the current with respect to a reference (standard) solar spectrum at 100 mW/cm^2 intensity. Reference cells are normally used to measure the intensity of the light source. However, the error in the current of the device under test is dependent on the spectral irradiance of the source and the reference spectrum, the test cell spectral response, and the reference cell spectral response. This error in the current can exceed 10% for many of the advanced material systems. Two procedures are described which reduce the error in the current to an acceptable level and allow the light source to be set to the correct intensity. The first procedure demonstrates that with the use of a calibrated reference cell and a spectral mismatch correction factor, the error in the current, and hence the efficiency, is reduced to a level less than 2%. In addition, a new method for calibrating reference cells with respect to a given reference spectrum is presented. This procedure for calibrating reference cells is independent of the reference cell or solar spectrum and allows reference cells to be calibrated with an accuracy of approximately 1%. The second procedure does not use a reference cell, but requires the measurement of the relative spectral response of the device under test and the absolute spectral irradiance of the light source in the test plane over the same wavelength range as the spectral response of the test cell. This method is limited by the accuracy of the spectral irradiance measurement which is about 5%.

REFERENCE CELL CALIBRATION

A PV reference cell is used to measure the intensity of the light source, and hence errors in obtaining the current and efficiency of a test device are proportional to the errors in the reference cell calibration. A reference cell can be calibrated with respect to an arbitrary reference (or "standard") spectrum ($E_R(\lambda)$) using the following equation (1):

$$CN = \frac{I_{sc}^{R,S}}{E_{tot}} \times \frac{\int_{0.3}^{4\mu m} E_R(\lambda) SR_R(\lambda) d\lambda}{\int_{0.3}^{4\mu m} E_R(\lambda) d\lambda} \times \frac{\int_{0.3}^{4\mu m} E_S(\lambda) d\lambda}{\int_{0.3}^{4\mu m} E_S(\lambda) SR_R(\lambda) d\lambda} \quad [1]$$

CN is known as the calibration number for a given reference cell and when multiplied by 100 mW/cm^2 gives the reference-cell short-circuit current under the normalized reference spectrum. The short-circuit current of the reference cell ($I_{sc}^{R,S}$), total irradiance (E_{tot}), and the solar spectral irradiance ($E_S(\lambda)$) are measured at the same time with the same field of view (FOV). A Kendal MK VI absolute active cavity radiometer with a 5° FOV was chosen to measure the total irradiance rather than a global pyranometer (180° FOV) because: (a) the accuracy is at least an order of magnitude better (± 0.5% vs ± 5%), (b) the FOV can be more easily matched to the reference cell and spectroradiometer, and (c) $E_S(\lambda)$ can be more accurately measured. A LI-COR

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LI-1800 spectroradiometer is used to measure the spectral irradiance, $E_S(\lambda)$, from 0.38 to 1.1 μm, while a direct normal computer model fit (2) to the LI-COR data is used for the ranges 0.3 to 0.38 μm and 1.1 to 4.0 μm. The extension of $E_S(\lambda)$ to the wavelength range 0.3 to 4.0 μm (the range of the reference spectrum, $E_R(\lambda)$) is essential to prevent CN from being approximately 20% low. The spectral response of the reference cell ($SR_R(\lambda)$) is measured by using a narrow bandwidth (10 nm) interference filter system (with a resolution of 20 nm in the visible and 50 nm in the infrared) to provide chopped monochromatic light, and with the intensity of a steady-state tungsten-halogen light bias set to give I_{sc} at 100 mW/cm^2. Note that systematic errors in $E_R(\lambda)$, $E_S(\lambda)$, and $SR_R(\lambda)$ cancel and do not appear in CN. The accuracy of CN is limited by the accuracy of E_{tot} and the measurement of $E_S(\lambda)$ to about 1%.

Table 1 lists the mean calibration number and standard deviation for six reference cells calibrated using Eq. [1] at 28°C with the global reference spectrum in Ref. 3. Depending on the spectral response of the reference cell (Fig. 1) the standard deviation of the mean corrected calibration number (<CN>) varied from 0.2 to 0.9%, which is about half the standard deviation of the mean uncorrected calibration number.

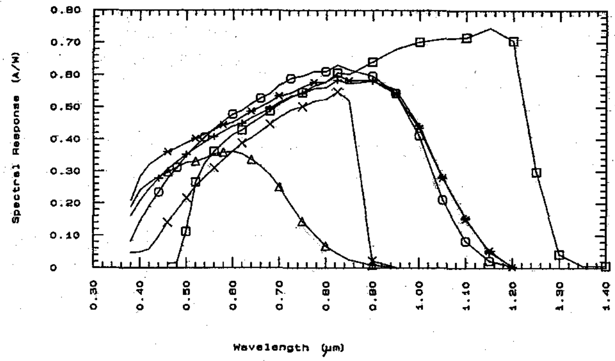

Figure 1. Spectral response of the reference cells S01(+), S04(*), Y265(O), S02(X), KG1(Δ), and S05($\square$).

Table 1. Summary of primary reference cell calibrations.

Cell	Type	$<I_{sc}^{R,S}/E_{tot}>$ (Uncorrected CN) (A/W/cm^2)	Standard Deviation (%)	<CN> (A/W/cm^2)	Standard Deviation (%)	Number of Measurements
S01	Si	1.2839	0.51	1.2811	0.26	7
S04	Si	1.3335	0.70	1.3327	0.20	9
Y265	Si	1.3419	0.64	1.3374	0.37	11
S02	GaAs	0.8079	0.86	0.8084	0.34	8
KG1	Filtered Si	0.6099	1.37	0.6081	0.22	8
S05	$Cd(Zn)S/CuInSe_2$	0.3362	1.40	0.3336	0.85	9

Table 2. Summary of reference cell calibration numbers with respect to various global and direct normal reference spectra.

		<CN> (A/W/cm^2)				
Cell	Type	Global(3)	Global(4)	Direct(5)	Direct(6)	Direct(7)
S01	Si	1.281	1.276	1.269	1.264	1.281
S04	Si	1.333	1.329	1.312	1.308	1.325
Y265	Si	1.337	1.329	1.329	1.322	1.342
S02	GaAs	0.808	0.797	0.796	0.799	0.809
KG1	Filtered Si	0.608	0.612	0.557	0.556	0.565
S05	$Cd(Zn)S/CuInSe_2$	0.334	0.329	0.349	0.347	0.351

Table 2 summarizes CN for the reference cells in Table 1 with respect to various reference spectra. The global reference spectra in Refs. 3 and 4 and the direct normal reference spectra in Refs. 5 and 6 have the same air mass, water vapor, turbidity, and ozone, and were generated with the same model; the difference is the AMO spectrum and some absorption coefficients. Notice that the choice of a direct or global reference spectrum has only a small effect on Si and GaAs. However, the calibration number for KG1 (representing an amorphous-silicon alloy cell) is about 10% higher for global compared to direct normal, while the calibration number for Cd(Zn)S/$CuInSe_2$ is about 5% lower for global compared to a direct normal reference spectrum.

SPECTRAL MISMATCH CORRECTIONS

The reference cell calibration numbers described above allow one to make intensity corrections when adjusting a light source. However, one must also take into account spectral mismatch corrections before measuring the correct short-circuit current of the test cell. The fractional error, known as the spectral mismatch factor, M, introduced because the reference cell spectral response ($SR_R(\lambda)$) differs from the spectral response of the device under test ($SR_T(\lambda)$), and the source spectral irradiance ($E_S(\lambda)$) differs from the reference spectral irradiance ($E_R(\lambda)$), can be computed as follows (1,8,9):

$$M = \frac{\int_{0.3}^{4\mu m} E_R(\lambda) SR_R(\lambda) d\lambda}{\int_{0.3}^{4\mu m} E_S(\lambda) SR_R(\lambda) d\lambda} \times \frac{\int_{0.3}^{4\mu m} E_S(\lambda) SR_T(\lambda) d\lambda}{\int_{0.3}^{4\mu m} E_R(\lambda) SR_T(\lambda) d\lambda} \qquad [2]$$

The measured short-circuit current of the test cell ($I_{sc}^{T,S}$) can then be corrected for spectral mismatch error to give $I_{sc}^{T,C}$ using:

$$I_{sc}^{T,C} = I_{sc}^{T,S} / M \qquad [3]$$

The usefulness of Eq. [3] to reduce the error in the short-circuit current with respect to standard test conditions was evaluated using the cells in Tables 1 and 2. Since the reference cells were calibrated in pairs, the fractional error between the calibrated value and the value using the other as a reference cell could be determined. These same pairs of cells were then evaluated indoors with a Spectrolab X-25 solar simulator (whose spectral irradiance is given in Fig. 2).

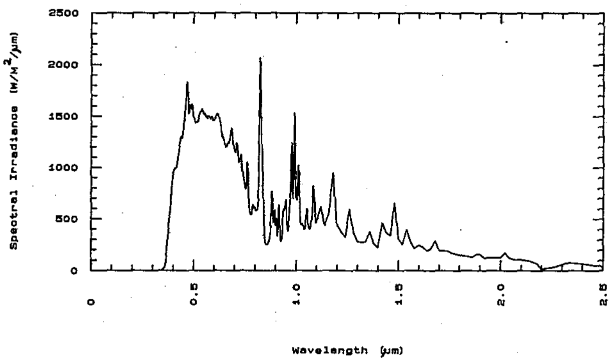

Figure 2. Absolute spectral irradiance of the Spectrolab X-25 solar simulator measured with a LI-COR LI-1800 spectroradiometer.

The fractional errors in the short-circuit current with and without a correction for spectral mismatch were determined and are summarized in Table 3. The use of Eq. [3] to correct for spectral mismatch reduced the error in the short-circuit current to less than 1% in almost all cases. (It should be noted that the short-circuit current readings for the cells in Table 3 have already been corrected for intensity to 100 mW/cm^2.)

Table 3. The use of the spectral mismatch index M to reduce the error in indoor and outdoor measurements of the short-circuit current using the reference-cell method.

		Outdoors			Spectrolab X-25		
Test Cell	Reference Cell	M	% Error $I_{sc}^{T,S}$	% Error $I_{sc}^{T,C}$	M	% Error $I_{sc}^{T,S}$	% Error $I_{sc}^{T,C}$
S04	Y265	1.0004	0.4	0.5	1.0078	-1.0	-0.2
KG1	Y265	1.0072	-1.3	-0.5	1.0548	-5.8	-0.3
KG1	S02	1.0062	-1.2	-0.6	1.0722	-7.6	-0.3
KG1	S05	0.9712	2.6	-0.2	0.9901	-0.1	1.0
S02	S01	1.0019	0.1	0.3	0.9773	2.4	0.2
S02	S04	0.9940	0.4	-0.2	0.9763	2.6	0.2
S02	S05	0.9854	2.7	1.2	0.9234	6.4	-1.3
S05	Y265	1.0132	-2.5	-1.2	1.0654	-6.1	0.4

LIGHT-SOURCE-INDEPENDENT METHOD

Another way to show that Eq. [3] is valid is to evaluate a test solar cell with many different reference cells and show that the same short-circuit current is obtained on different solar simulators. These results, summarized in Tables 4 and 5, show that a mean $I_{sc}^{T,R}$ of 4.16 mA is obtained for the amorphous-silicon alloy sample L746 (whose $SR_T(\lambda)$ is shown in Fig. 3), with a standard deviation of less than 1% (measured at 25°C, and using the reference spectrum of Ref. 3). The spectral irradiance of the Optical Radiation Corporation simulator used in Table 4 is shown in Fig. 4. The measured short-circuit current of the test cell ($I_{sc}^{T,S}$) under some light source (the source spectrum) is corrected for both spectral mismatch (M) and intensity using the following expression:

$$I_{sc}^{T,R} = \left[\frac{I_{sc}^{T,S}}{M} \right] \times \left[\frac{I_{sc}^{R,R}}{I_{sc}^{R,S}} \right] \qquad [4]$$

Here $I_{sc}^{R,R}$ is the short-circuit current of the reference cell under the reference spectrum (which is just the calibration number, CN, of the primary reference cell times 100 mW/cm^2) and $I_{sc}^{R,S}$ is the measured short-circuit current of the reference cell under the source spectrum. Then, $I_{sc}^{T,R}$ is the short-circuit current of the test cell under the reference spectrum, i.e., the measured short-circuit current corrected for both spectral mismatch and intensity.

Tables 4 and 5 show results using one test cell and several reference cells. In practice, one would normally have only one calibrated reference cell with many test cells. Therefore, we have applied this method in our photovoltaics research laboratory to measure several test cells. In addition, we have compared six different solar simulators to show that this technique, although dependent on having a calibrated reference cell, is light-source independent. The results are shown in Table 6. The reference spectrum used was the SERI/ASTM standard global solar spectrum as cited in Ref. 3.

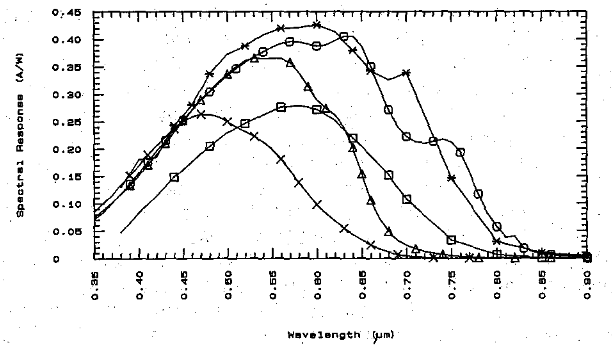

Figure 3. Absolute spectral response of four amorphous-silicon alloy test cells (thin a-Si alloy (X), thick a-Si alloy (Δ), a-Si:Ge alloy (O), L746 (*)) and a filtered silicon reference cell (□).

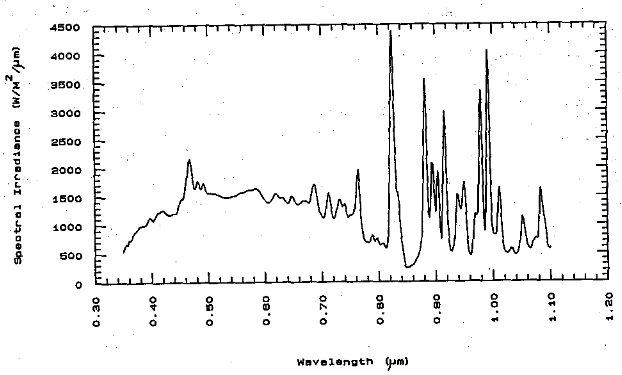

Figure 4. Spectral irradiance of an Optical Radiation Corporation solar simulator.

Table 4. Amorphous-silicon alloy test cell L746 measured under an Optical Radiation Corporation solar simulator with several reference cells.

	Reference Cell Measurements			L746 Test Cell ($I_{sc}^{T,S}$ (meas.) = 4.50 mA)
	$I_{sc}^{R,R}$	$I_{sc}^{R,S}$		($I_{sc}^{T,R}$)
Ref. Cell	(CN * 100 mW/cm^2) (From Table 1) (mA)	(Meas. under ORC) (mA)	M	Spectral Mismatch and Intensity Corrected (mA)
S01	128.11	164.1	0.8494	4.136
S04	133.27	169.5	0.8567	4.130
Y265	133.74	168.2	0.8535	4.192
S02	80.84	88.2	0.9721	4.243
KG1	60.81	66.1	0.9955	4.158

Mean $I_{sc}^{T,R}$ = 4.17 mA; standard deviation = 1.0%.

Table 5. Amorphous-silicon alloy test cell L746 measured under a Spectrolab X-25 solar simulator with several reference cells.

	Reference Cell Measurements			L746 Test Cell ($I_{sc}^{T,S}$ (meas.) = 4.046 mA)
	$I_{sc}^{R,R}$	$I_{sc}^{R,S}$		($I_{sc}^{T,R}$)
Ref. Cell	(CN * 100 mW/cm^2) (From Table 1) (mA)	(Meas. under X-25) (mA)	M	Spectral Mismatch and Intensity Corrected (mA)
S01	128.11	118.4	1.0545	4.152
S04	133.27	123.4	1.0533	4.148
Y265	133.74	122.6	1.0615	4.158
S02	80.84	72.9	1.0790	4.158
KG1	60.81	59.0	1.0063	4.144

Mean $I_{sc}^{T,R}$ = 4.15 mA; standard deviation = 0.1%

Table 6. Use of the calibrated-reference-cell method to obtain the corrected short-circuit current for three different amorphous-silicon alloy test cells under six different solar simulators.

Test Cell	Solar Simulator (Source Spectrum)	Test Cell $I_{sc}^{T,S}$ (mA) (Measured)	Ref. Cell $I_{sc}^{R,S}$ (mA) (Measured)	Spectral Mismatch Parameter (M)	Test Cell $I_{sc}^{T,R}$ (mA) (Corrected)
		($I_{sc}^{R,R}$ = CN * 100 = 36.97 mA)			
Cell # 1 (a-Si:Ge)	ORC #1	4.69	41.0	1.0072	4.199
	ORC #2	4.68	41.0	0.9817	4.299
	ORC #3	4.42	37.9	0.9798	4.400
	ORC #4	3.95	34.2	0.9867	4.327
	Oriel	4.49	38.0	1.0099	4.325
	Spectrolab XT-10	4.14	34.8	1.0112	4.349
	Mean $I_{sc}^{T,R}$ = 4.317		standard deviation = 1.55%		
Cell # 2 (thin a-Si)	ORC #1	2.10	41.0	0.9759	1.940
	ORC #2	2.15	41.0	0.9773	1.984
	ORC #3	2.03	37.9	0.9998	1.981
	ORC #4	1.91	34.2	1.0519	1.963
	Oriel	2.02	38.0	0.9775	2.010
	Spectrolab XT-10	1.81	34.8	1.0059	1.912
	Mean $I_{sc}^{T,R}$ = 1.965		standard deviation = 1.77%		
Cell # 3 (thick a-Si)	ORC #1	3.30	41.0	0.9855	3.019
	ORC #2	3.43	41.0	0.9935	3.113
	ORC #3	3.23	37.9	1.0036	3.139
	ORC #4	2.91	34.2	1.0216	3.079
	Oriel	3.17	38.0	0.9842	3.134
	Spectrolab XT-10	2.86	34.8	0.9933	3.059
	Mean $I_{sc}^{T,R}$ = 3.091		standard deviation = 1.52%		

The short-circuit current of the three different amorphous-silicon alloy test cells (column 1) were measured (column 3) under six different solar simulators (column 2). A calibrated reference cell with a CN of 0.3697 ($SR_R(\lambda)$ given in Fig. 3, □) was also measured (column 4) in the same test plane, taking spatial and temporal variations in light intensity into account. The spectral mismatch factor, M, was calculated (column 5) from Eq. [2] and then Eq. [4] was used to correct the measured short-circuit current of the test cell for both spectral mismatch and intensity (column 6). Note that for each test cell the mean $I_{SC}^{T,R}$ has a standard deviation of less than 2% using this method. In the actual application of this method in the laboratory, the solar simulator is at this point adjusted to give the mean $I_{SC}^{T,R}$, and it is then considered "calibrated" to this particular reference spectrum for this test cell. The device I-V curve can now be measured, giving the cell I-V parameters, J_{SC}, V_{OC}, ff, P_{max}, and hence the cell conversion efficiency.

REFERENCE-CELL-INDEPENDENT METHOD

The second calibration procedure omits the two integrals involving $SR_R(\lambda)$ in Eq. [2] and requires absolute $E_S(\lambda)$ measurements (10). This procedure does not use a reference cell. In addition, note that systematic errors in $SR_T(\lambda)$ will still cancel. Using this revised form for the spectral mismatch correction (M') for cell L746 gives 4.01 mA for the X-25 solar simulator ($M' = 1.0088$) and 4.14 mA for the ORC simulator ($M' = 1.0871$). These are within 4% of the mean $I_{SC}^{T,R}$ found in Tables 4 and 5. This difference is within the calibration error of the spectroradiometer and is less than the error would have been had the intensity been measured with just a silicon reference cell or a global pyranometer and not correcting for spectral mismatch errors. Integrating the absolute spectral response for sample L746 directly with $E_R(\lambda)$ in Ref. 3 yields a current at 100 mW/cm^2 of 4.34 mA which is 4% higher than the more accurate current found in Tables 4 and 5.

SUMMARY

In conclusion, a method has been presented which shows that the short-circuit current, and hence efficiency, of a solar cell can be measured, using calibrated reference cells, with an error of less than 2% under standard test conditions, independent of the light source used. This method involves calibrating reference cells using Eq. [1], calculating spectral mismatch using Eq. [2], and then applying both spectral mismatch and intensity corrections with Eq. [4] to obtain the corrected short-circuit current value. A less accurate method which does not require a reference cell can be used to measure the short-circuit current within approximately 5% if accurate absolute spectral response measurements of the test cell can be made, or if the relative spectral response and the absolute spectral irradiance measurement of the light source (in the test plane) can be performed. Both of these techniques for obtaining corrected short-circuit current are preferred over other, less accurate, methods (such as using a global pyranometer or a reference cell without correcting for spectral mismatch errors). Thus, persons interested in measuring photovoltaic conversion efficiencies under standard test conditions should use either one or both of these calibration techniques so that accurate solar cell efficiencies can be obtained from, and compared among, devices of various structures and compositions.

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