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Standard Test Methods for Measurement of Electrical Performance and Spectral Response of Nonconcentrator Multijunction Photovoltaic Cells and Modules[1]

1. Scope

1.1 These test methods provide special techniques needed to determine the electrical performance and spectral response of two-terminal, multijunction photovoltaic (PV) devices, both cell and modules.

1.2 These test methods are modifications and extensions of the procedures for single-junction devices defined by Test Methods E948, E1021, and E1036.

1.3 These test methods do not include temperature and irradiance corrections for spectral response and current-voltage (I-V) measurements. Procedures for such corrections are available in Test Methods E948, E1021, and E1036.

1.4 These test methods may be applied to cells and modules intended for concentrator applications.

1.5 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E772 Terminology of Solar Energy Conversion
E927 Specification for Solar Simulation for Photovoltaic Testing
E948 Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight
E973 Test Method for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell
E1021 Test Method for Spectral Responsivity Measurements of Photovoltaic Devices
E1036 Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells
E1040 Specification for Physical Characteristics of Nonconcentrator Terrestrial Photovoltaic Reference Cells
E1125 Test Method for Calibration of Primary Non-Concentrator Terrestrial Photovoltaic Reference Cells Using a Tabular Spectrum
E1328 Terminology Relating to Photovoltaic Solar Energy Conversion (Withdrawn 2012)[3]
E1362 Test Method for Calibration of Non-Concentrator Photovoltaic Secondary Reference Cells
G138 Test Method for Calibration of a Spectroradiometer Using a Standard Source of Irradiance
G173 Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface

3. Terminology

3.1 *Definitions*—definitions of terms used in this standard may be found in Terminology E772 and in Terminology E1328.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *multijunction device, n*—a photovoltaic device composed of more than one photovoltaic junction stacked on top of each other and electrically connected in series.

3.2.2 *component cells, n*—the individual photovoltaic junctions of a multijunction device.

3.3 *Symbols:*

[1] These test methods are under the jurisdiction of ASTM Committee E44 on Solar, Geothermal and Other Alternative Energy Sources and is the direct responsibility of SubcommitteeE44.09 on Photovoltaic Electric Power Conversion.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.

C = reference cell calibration constant under the reference spectrum, $A{\cdot}m^2{\cdot}W^{-1}$
E_o = total irradiance of reporting conditions, $W{\cdot}m^{-2}$
$E_S(\lambda)$ = source spectral irradiance, $W{\cdot}m^{-2}{\cdot}nm^{-1}$ or $W{\cdot}m^{-2}{\cdot}\mu m^{-1}$
$E_R(\lambda)$ = reference spectral irradiance, $W{\cdot}m^{-2}{\cdot}nm^{-1}$ or $W{\cdot}m^{-2}{\cdot}\mu m^{-1}$
FF = fill factor, dimensionless
i = subscript index associated with an individual component cell
I_o = current of test device under the reference spectrum, A
I = current of test device under the source spectrum, A
I_{sc} = short-circuit current, A
I_R = short-circuit current of reference cell under the source spectrum, A
M = spectral mismatch parameter, dimensionless
n = number of component cells in the multijunction device
P_{max} = maximum power, W
$Q(\lambda)$ = quantum efficiency, dimensionless
$R(\lambda)$ = spectral response, $A{\cdot}W^{-1}$
$R_T(\lambda)$ = test device spectral response, $A{\cdot}W^{-1}$
$R_R(\lambda)$ = reference cell spectral response, $A{\cdot}W^{-1}$
T = temperature, °C
V_{oc} = open-circuit voltage, V
V_b = voltage applied by dc bias source, V
Z = current balance, dimensionless
λ = wavelength, nm or µm

4. Significance and Use

4.1 In a series-connected multijunction PV device, the incident total and spectral irradiance determines which component cell will generate the smallest photocurrent and thus limit the current through the entire series-connected device. This current-limiting behavior also affects the fill factor of the device. Because of this, special techniques are needed to measure the correct I-V characteristics of multijunction devices under the desired reporting conditions (see Test Methods E1036).

4.2 These test methods use a numerical parameter called the current balance which is a measure of how well the test conditions replicate the desired reporting conditions. When the current balance deviates from unity by more than 0.03, the uncertainty of the measurement may be increased.

4.3 The effects of current limiting in individual component cells can cause problems for I-V curve translations to different temperature and irradiance conditions, such as the translations recommended in Test Methods E1036. For example, if a different component cell becomes the limiting cell as the irradiance is varied, a discontinuity in the current versus irradiance characteristic may be observed. For this reason, it is recommended that I-V characteristics of multijunction devices be measured at temperature and irradiance conditions close to the desired reporting conditions.

4.4 Some multijunction devices have more than two terminals which allow electrical connections to each component cell. In these cases, the special techniques for spectral response measurements are not needed because the component cells can be measured individually. However, these I-V techniques are still needed if the device is intended to be operated as a two-terminal device.

4.5 Using these test methods, the spectral response is typically measured while the individual component cell under test is illuminated at levels that are less than E_o. Nonlinearity of the spectral response may cause the measured results to differ from the spectral response at the illumination levels of actual use conditions.

5. Summary of Test Methods

5.1 Spectral response measurements of the device under test are accomplished using light- and voltage-biasing techniques of each component cell, followed by determination of the spectral response according to Test Methods E1021.

5.2 If a spectrally adjustable solar simulator is available (see 6.1.1) the electrical performance measurements use an iterative process of adjusting the incident spectral irradiance until the operating conditions are close to the desired reporting conditions is used. This adjustment modifies a quantity known as the current balance. The I-V characteristics are then measured according to Test Methods E948 or E1036. Appendix X1 contains a derivation and discussion of current balance.

5.3 For the case of light sources where the spectral irradiance cannot be changed, such as outdoors or if a spectrally adjustable solar simulator is not available, the I-V characteristics are measured according to Test Methods E948 or E1036. However, the current balance in each component cell must also be determined and reported.

6. Apparatus

6.1 In addition to the apparatus required for Test Methods E948, E973, E1021, E1036, and G138, these test methods refer to the following apparatus.

6.1.1 *spectrally adjustable Solar Simulator*—A solar simulator that meets the requirements of Specification E927 and which has the additional capability of allowing different wavelength regions of its spectral irradiance to be independently adjusted. This may be accomplished by several methods, such as a multisource simulator with independent sources for different regions, or a multiple filter simulator.

6.1.1.1 Ideally, the adjustable wavelength ranges of the spectrally adjustable solar simulator should correspond to the spectral response ranges of each component cell in the multijunction device to be tested.

6.1.2 *Reference Cells*—Photovoltaic reference cells (see Specification E1040), calibrated according to Test Methods E1125 or E1362, are used to measure source irradiance in the wavelength regions that correspond to each component cell in the multijunction device to be tested. For best results, the spectral responses of the reference cells should be similar to the spectral responses of the corresponding component cells.

6.1.3 *Bias Light Source*—A dc bias light as specified by Test Methods E1021, that is equipped with appropriate spectral filters to block wavelength regions corresponding to the expected spectral response range of the individual component cell being tested.

6.1.3.1 Acceptable alternatives to filtered light sources are continuous lasers that emit at single wavelengths in the spectral response ranges of each component cell. Ideally, the selected laser wavelengths should not illuminate regions where the spectral responses of any two component cells overlap.

6.1.4 *Bias Voltage Source*—A variable dc power supply capable of providing a voltage equal to the open-circuit voltage of the multijunction device to be tested, and compatible with the synchronous detection instrumentation of Test Methods E1021.

7. Procedure

7.1 *Spectral Response:*

7.1.1 Place the device under test in the spectral response test fixture.

7.1.2 Select the component cell to be measured.

7.1.3 Apply light bias to component cells not being measured using the bias light source:

7.1.3.1 Choose spectral filters whose spectral transmittance, when combined, corresponds to the spectral response of the component cell or cells not being measured. Install the spectral filters in front of the bias light source.

7.1.3.2 If lasers are used, turn on the lasers that emit wavelengths corresponding to the component cell or cells not being measured.

7.1.3.3 Ideally, the illumination on the component cell being measured should be at E_o and the component cells not being measured should be illuminated at higher levels. Practically, the component cell to be measured should have some illumination, as device spectral responsivities can be a function of the illumination level.

7.1.3.4 Turn on the bias light source and illuminate, as a minimum, the region where the monochromatic beam illuminates the test device.

7.1.4 Measure the V_{oc} of the test device.

7.1.5 Calculate the bias voltage to use during the test:

7.1.5.1 For devices with component cells that contribute similar voltages, calculate the bias voltage according to Eq 1.

$$V_b = \frac{n-1}{n} V_{oc}. \tag{1}$$

7.1.5.2 For devices with component cells contributing substantially different voltages, calculate the bias voltage as the sum of the expected voltage contributions from the component cells not being measured.

7.1.6 Set the V_b on the bias voltage source.

7.1.7 Connect the test device to the ac measurement instrumentation.

7.1.8 Maximize the ac signal from the component cell under test using a wavelength at which it is expected to respond:

7.1.8.1 Set the monochromatic light source to a wavelength in the expected spectral response region of the component cell to be measured.

7.1.8.2 Adjust the bias light intensity to saturate or maximize the test device signal.

7.1.9 Minimize the test device signal at wavelengths where the component cells not being measured are expected to respond:

7.1.9.1 Set the monochromatic light source for a wavelength in the expected spectral response region of the component cell not being measured.

7.1.9.2 Minimize or zero the test device signal by adjusting the bias light intensity.

7.1.9.3 Repeat 7.1.9.1 and 7.1.9.2 for additional component cells not being measured, if any.

7.1.10 As in 7.1.8 and 7.1.9, adjust V_b to further maximize the signal in 7.1.8 and further minimize the signal in 7.1.9.

7.1.11 Select light bias and voltage bias levels that both maximize the signal in 7.1.8 and minimize the signal in 7.1.9. The signal in 7.1.9 should correspond to a quantum efficiency, $Q(\lambda)$, that is less than 0.01 in wavelength regions where the component cell being measured is known to have no response.

7.1.12 It may be necessary to adjust the bias light source in 7.1.3 to obtain a light bias condition that satisfies 7.1.11.

7.1.13 Measure the relative spectral response of the component cell being tested according to Test Methods E1021.

7.1.14 Repeat 7.1.2 – 7.1.13 for each component cell of the multijunction device under test.

7.2 *Electrical Performance, spectrally adjustable Solar Simulator:*

7.2.1 Adjust the total irradiance of the spectrally adjustable solar simulator to a level close to the desired reporting conditions using a reference cell or previous experience (this initial irradiance level is not critical).

7.2.2 Measure the spectral irradiance of the spectrally adjustable solar simulator with a spectroradiometer calibrated according to Test Method G138.

7.2.3 Calculate the spectral mismatch parameter, M_i, for each component cell in the multijunction device under test using the spectral responses obtained in 7.1, the reference cell spectral responses, the spectral irradiance measured in 7.2.2, and the desired reference spectral irradiance (such as Tables G173).

7.2.4 Measure the I_{sc} of each reference cell under the spectrally adjustable solar simulator, I_{Ri}, in the same test plane as the multijunction device under test.

7.2.5 Calculate the current balance, Z_i, for each component cell in the multijunction device under test using the following equation:

$$Z_i = \frac{1}{M_i} \frac{E_O C_i}{I_{Ri}} \tag{2}$$

7.2.6 If the current balance for each cell is within 1.00±0.03, the spectrally adjustable solar simulator is adjusted to within reasonable limits. If not, adjust the spectral irradiance and repeat 7.2.2 – 7.2.5.

7.2.6.1 Ideally, to minimize spectral errors, each current balance should be within 1.00±0.01, although the number of iterations required to obtain this degree of balance may be prohibitive.

7.2.6.2 It should be noted that for intermediate iterations, it is possible to omit the spectral irradiance measurement of 7.2.2 and substitute the spectral irradiance measured for previous iterations, especially if only small changes have been made. However, the measurement should not be omitted for the final iteration of 7.2.2 – 7.2.5.

7.2.7 Mount the multijunction device under test in the I-V measurement test fixture and determine its I-V characteristics according to Test Methods E948, Sections 7 and 8, or E1036, Sections 7 and 8, as appropriate.

7.2.7.1 Because the spectral irradiance has been adjusted to minimize spectral errors, the irradiance and spectral mismatch corrections specified in Test Methods E948 and E1036 are not needed.

7.3 *Electrical Performance, Non-spectrally adjustable Light Source:*

7.3.1 If possible, set the total irradiance of the set light source to a level close to that of the desired reporting conditions.

7.3.2 Measure the spectral irradiance of the test light source with a spectroradiometer calibrated according to Test Method G138.

7.3.3 Measure the I_{sc} of each reference cell under the test light source, I_{Ri}, in the same test plane as the multijunction device under test.

7.3.4 Calculate the spectral mismatch parameter, M_i, for each component cell in the multijunction device under test using the spectral responses obtained in 7.1, the reference cell spectral responses, the spectral irradiance measured in 7.3.2, and the desired reference spectral irradiance (such as Tables G173).

7.3.5 Calculate the current balance, Z_i, for each component cell in the multijunction device under test using Eq 2.

7.3.6 Mount the multijunction device under test in the I-V measurement test fixture and determine its I-V characteristics according to Test Methods E948, Sections 7 and 8, or E1036, Sections 7 and 8, as appropriate.

7.3.6.1 Perform the irradiance and spectral mismatch corrections specified in Test Methods E948 and E1036 using the reference cell calibration factor and spectral mismatch parameter for one of the component cells in the multijunction device under test. Ideally the selected cell should be the cell that limits the current through the multijunction device when illuminated by $E_R(\lambda)$.

8. Report

8.1 In addition to the reporting requirements of Test Methods E948, E1021, and E1036, report as a minimum the following data and information:

8.1.1 *Spectral Response*—A description of the measurement system, and for each component cell, the dc bias light current density, a description of the bias light used, including light sources and filters, and the bias voltage level.

8.1.2 *Electrical Performance*—A description of the measurement system, and the current balance and spectral mismatch parameters, Z_i and M_i, for each component cell.

8.1.2.1 If a non-spectrally adjustable light source was used, report which component cell was selected for the irradiance and spectral mismatch corrections in 7.3.6.1.

9. Precision and Bias

9.1 The spectral response and I-V measurement procedures described by these test methods are extensions of the procedures in Test Methods E948, E1021, and E1036 and are therefore subject to the precision and bias provisions of these test methods.

9.2 The extent to which the precision and bias of the results obtained using this test method are degraded will depend on how well the iterative procedures in 7.1 and 7.2 are used to match the desired reporting conditions.

9.3 For I-V measurements obtained without a spectrally adjustable solar simulator (see 7.3), it is not possible to simulate the desired reporting conditions. In these cases, error may be introduced, in both the I_{sc} and FF results, by current imbalances caused by the spectral irradiance of the test light source.

9.4 In both cases, the deviation of the current balance values Z_i from unity will give a numerical indication of the quality of the I-V measurements and of the possible error introduced.

10. Keywords

10.1 Solar Energy; Photovoltaics; Multijunction Devices; Electrical Performance; Spectral Response

APPENDIX

(Nonmandatory Information)

X1. DISCUSSION OF CURRENT BALANCE

X1.1 An ideal goal of photovoltaic electrical performance measurements is to illuminate the device under test with a spectral irradiance that is identical to the desired reference spectral irradiance. Because a solar simulator with a perfect spectral irradiance cannot be constructed, performance measurements of single junction use the spectral mismatch parameter, M, defined by equation 1 of Test Method E973, to correct the error caused by the imperfect spectral irradiance.

X1.2 To correct the measured current for spectral mismatch, equation 1 of Test Method E948 is used.

X1.3 For multijunction photovoltaic devices, the goal is the same, but the situation is complicated by the additional semiconductor device junctions (which are referred to as component cells in this test method). In order to measure the correct I-V characteristics, it is necessary for the number of electron-hole pairs generated in each junction by the incident photons be the same as would be generated if the multijunction device were illuminated by an ideal solar simulator. The iterative spectral irradiance adjustment procedure in 7.2 is designed to achieve this goal.

X1.4 If the temperature correction term is neglected, equation 1 of Test Method E948 can be rewritten as:

$$\frac{I_{oi}}{I_i} = \frac{1}{M_i} \frac{E_o C}{I_{Ri}} = Z_i \quad \text{(X1.1)}$$

which is identical to Eq 2 and is the definition of current balance. A current balance value will be associated with each component cell.

X1.5 Note that, from Eq X1.1, if the current balance is equal to unity, the current of the device under test must be equal to its value under the reference spectrum, even if neither of these values are actually known. Because the only independently adjustable variable in Eq X1.1 is the spectral irradiance of the test light source (see equation 1 of Test Method E973), adjustment of the spectral irradiance is the only way to change the current balances.

X1.6 If the spectral irradiance can be modified only in the spectral bands corresponding to the spectral response regions of the component cells without affecting the other spectral response regions, it can be seen that the adjustment process will be much easier.

X1.7 Note that it may be possible to perform the adjustment procedure with a single reference cell if the spectral response of the cell spans all the wavelength regions of the component cells in the multijunction devices. However, a similar recommendation to that of X1.6 can be made in this case — if independent reference cells corresponding to each component cell are available, the current balancing will be easier.

X1.8 For the cases of measurements made outdoors and with non-spectrally adjustable solar simulators, the current balances cannot be independently changed. The best that can be done is to simply report the current balances as an indication of the quality of the measurements. Note that for outdoor measurements, the time of day or the season may provide spectral irradiance conditions that give better current balance values.