Designation: E 2236 – 02

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

This standard is issued under the fixed designation E 2236; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

## 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 E 948, E 1021, and E 1036.

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 E 948, E 1021, and E 1036.

1.4 These test methods apply only to nonconcentrator terrestrial multijunction photovoltaic cells and modules.

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

1.6 There is no similar or equivalent ISO standard.

1.7 *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:*

E 772 Terminology Relating to Solar Energy Conversion[2]

E 927 Specification for Solar Simulation for Terrestrial Photovoltaic Testing[2]

E 948 Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight[2]

E 973 Test Method for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell[2]

E 1021 Test Methods for Measuring Spectral Response of Photovoltaic Cells[2]

E 1036 Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells[2]

E 1039 Test Method for Calibration of Silicon Non-Concentrator Photovoltaic Primary Reference Cells Under Global Irradiation[2]

E 1040 Specification for Physical Characteristics of Nonconcentrator Terrestrial Photovoltaic Reference Cells[2]

E 1125 Test Method for Calibration of Primary Non-Concentrator Terrestrial Photovoltaic Reference Cells Using a Tabular Spectrum[2]

E 1328 Terminology Relating to Photovoltaic Solar Energy Conversion

E 1362 Test Method for Calibration of Non-Concentrator Photovoltaic Secondary Reference Cells[2]

G 138 Test Method for Calibration of a Spectroradiometer Using a Standard Source of Irradiance[3]

G 159 Tables for References Solar Spectral Irradiance at Air Mass 1.5: Direct Normal and Hemispheric for a 37° Tilted Surface[3]

## 3. Terminology

3.1 *Definitions*—definitions of terms used in this standard may be found in Terminology E 772 and in Terminology E 1328.

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:*

$C$ = reference cell calibration constant under the reference spectrum, $A \cdot m^2 \cdot W^{-1}$

[1] This test method is 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.

Current edition approved Oct. 10, 2002. Published January 2003.

[2] *Annual Book of ASTM Standards,* Vol 12.02.

[3] *Annual Book of ASTM Standards,* Vol 14.04.

$E_o$ = 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
$\lambda$ = 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 E 1036).

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 E 1036. 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 E 1021.

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 E 948 or E 1036. 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 E 948 or E 1036. 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 E 948, E 973, E 1021, E 1036, and G 138, these test methods refer to the following apparatus.

6.1.1 *spectrally adjustable Solar Simulator*—A solar simulator that meets the requirements of Specification E 927 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 E 1040), calibrated according to Test Methods E 1039, E 1125, or E 1362, 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 E 1021, 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.