test methods and devices rely on the assumption that the reference component cells are representative of the properties of the multi-junctions PV devices under test.

Multi-junction PV devices for terrestrial application were so far mainly developed as thin film compounds. Nowadays, emerging technology such as tandem perovskite/silicon cells for example yield very promising efficiencies and promise production at low cost. Their characterization during industrial production must be performed at a reasonable cost and must be technically easy to implement. The characterization method requires a light source that is stable for a sufficiently long time, longer than the intrinsic stabilization time of the device under test, which typically cannot be achieved with a Xenon flash lamp but can with an LED based light source. The light source must have a spectrum that is close enough to the AM1.5, as defined in the international standard IEC 60904-3 and the measurement method must satisfy procedures defined in the international standard IEC 60904-1 and IEC 60904-1-1.

The international standard IEC 60904-3 is described in the following website: https://webstore.iec.ch/publication/64682. The international standard IEC60904-1-1 is described in the following website: https://webstore.iec.ch/publication/29335.

Therefor there is a need for characterization methods during industrial production of multi-junction PV cells that must be provided at a low cost and high speed, with an apparatus technically easy to implement.

Summary of the invention

The proposed test method and test apparatus of the claimed invention solves the challenge of implementing a characterization method at reasonable cost with an apparatus and adjustment method that can characterize the IV curve of a multi-junction device. Additionally, it can extract the mismatch of its junction currents under illumination according to said international standard AM1.5, without using single junctions and/or calibrated reference cells or by measuring additionally the spectral response or quantum efficiency of the device. It takes advantage of the excellent spectral match of a pulsed, and filtered light source approaching the reference sunlight spectrum, according to the norm AM1.5, and combines it with at least two narrow

bandwidth light sources that can deliver light intensities over a time period as required for stabilized measurement of the individual junctions. Such light sources can be realized for example by LED arrays. The pulsed light source is preferably a pulsed Xenon light source.

There is disclosed a method to test multi-junction solar cells, preferably double-junction solar cells. More precisely the method of the claimed invention comprises the following steps.

There is disclosed a test apparatus configured to test multi-junction solar cells.

According to a first aspect of the present invention, there is provided a method of measuring and calculating a current-voltage curve (IV) and a current mismatch between junctions of a tandem solar cell, comprising at least two solar subcells, is performed under simulated solar irradiance according to the illumination norm AM1.5, as defined in the international standard IEC 60904-3, and comprising the steps (A-L) of:

A) providing at least one first light source for providing a light beam that has a spectrum corresponding to the international standard AM 1.5, as defined in the international standard IEC 60904-3;

B) providing at least two narrow bandwidth light sources for providing at least two different light beams, each light beam being predominately absorbed by one of the at least two sub-cells;

C) illuminating the tandem solar cell with said first light source, for acquiring its short-circuit current Isc;

D) Illuminating the tandem solar cell with said first light source and at the same time adding additional light step intensities by one of said at least a second and a third light sources, for acquiring offset values of the change of short-circuit current relative to the acquired reference short- circuit current;

E) realizing a first interpolation curve using current data acquired at low additional light intensity steps during the illumination **step D**;

F) realizing a second interpolation curve using high additional light intensity steps during said illumination **step D**;

G) defining the intersection of said first and second interpolation curves, said intersection defining a balance ratio Bal_{12} of the first and second junction short circuit current equal to 1;

H) calculating the short-circuit current of the tandem solar cell at said intersection;

I) determining the mismatch junctions (Bal12), ref of current between the; from the parameter determined in **Step H**;

J) repeating **Step D to I** without illumination by said first light source and by using only said second and said third light sources;

K) Calculating the necessary light intensities of said second and said third light sources, to achieve an identical balance ratio and identical short circuit current by using adapted gains for the second and third light sources, so that the combination of said second and third light sources provide the same test results of the solar cell as when illuminated with said first light source only;

L) Using a light source that is the optical combination of said light sources second and third light sources, according to **step K**, to illuminate a solar cell to be tested and providing the current-voltage curve I-V of the tandem solar cell.

In an embodiment said first and said second interpolation is a linear interpolation.

In an embodiment more than 2 different narrow band light sources possibly at least 4, possibly at least 5, even more possibly at least 6 narrow band light sources.

In an embodiment first light source is an optically filtered Xenon flash lamp having a spectrum close to the AM 1.5 light spectrum.

In an embodiment said at least two narrow band width light sources comprise light emitting diodes or light emitting diode arrays, the emitted light of said second light source being predominately absorbed in a first junction and the emitted light of said third light source being predominately absorbed in a second junction of the tandem solar cell under test.

In an embodiment the absolute and relative light intensities of the light sources are measured and/or controlled by optically filtered PV monitor cells. The individual monitor cell being only sensitive to the spectrum of the light source to be monitored.

In an embodiment additional steps are performed that consist in calculating solar cell parameters chosen among : acquired IV curve as of short circuit current, the open circuit voltage, the fill factor, the series resistance and the parallel resistance or a combination of them.

In embodiments the time to characterize a tandem solar cell is performed in less than 1 min, preferably less than 10 seconds, more preferably less than 5 seconds, even less than 0.15 seconds.

According to a second aspect of the present invention, there is provided a solar cell test apparatus for characterizing a tandem solar cell comprising at least two sub-cells. The test apparatus is configured to realize the method as defined in the first aspect. The test apparatus of the claimed invention comprises at least one first light source for providing a light beam that has a spectrum corresponding to the international standard AM1.5 and wherein the test apparatus comprises further:

- at least two narrow bandwidth light sources, for providing at least two different light beams, each light beam being predominately absorbed by one of the at least two sub-cells.

Claims

1. Method of measuring and calculating a current-voltage curve (IV) and a current mismatch between junctions of a tandem solar cell, comprising at least two solar subcells, the method being performed under simulated solar irradiance according to the illumination norm AM1.5, as defined in the international standard IEC 60904-3, and comprising the steps (A-L) of:

A) providing at least one first light source for providing a light beam that has a spectrum corresponding to the international standard AM 1.5, as defined in the international standard IEC 60904-3;

B) providing at least two narrow bandwidth light sources, for providing at least two different light beams, each light beam being predominately absorbed by one of the at least two sub-cells;

C) illuminating the tandem solar cell with said first light source, for acquiring its short-circuit current (Isc);

D) Illuminating the tandem solar cell with said first light source and at the same time adding additional light step intensities by one of said at least a second and a third light sources, for acquiring offset values of the change of short-circuit current (δ Isc) relative to the acquired reference short- circuit current;

E) realizing a first interpolation curve using current data acquired at low additional light intensity steps during the illumination step D;

F) realizing a second interpolation curve using high additional light intensity steps during said illumination step D;

G) defining the intersection of said first and second interpolation curves , said intersection defining a balance ratio Bal_{12} of the first and second junction short circuit current equal to 1;

H) calculating the short-circuit current Iscmatch of the tandem solar cell at said intersection

I) determining the mismatch junctions of current between the from the parameter determined in Step H;

J) repeating Step D to I without illumination by said first light source and by using only said second and said third light sources;

K) Calculating the necessary light intensities of said second and said third light sources, to achieve an identical balance ratio Bal12 (S2) = Bal12(S1) and identical short circuit current Isc(S2)= Isc(S1) by using adapted gains for the light sources, so that the combination of said light sources provide the same test results of the solar cell as when illuminated with said first light source S1 only;

L) Using a light source that is the optical combination of said light sources according to step K, to illuminate a solar cell to be tested and providing the current-voltage curve I-V of the tandem solar cell.

2. Method according to claim 1 wherein said first and said second interpolation is a linear interpolation.

3. Method according to claim 1 or claim 2 wherein more than 2 different narrow band light sources ($S2_N$) are used, N possibly being at least 4, possibly at least 5, even more possibly at least 6.

4. Method according to any one of claims 1 to 3 wherein the first light source is an optically filtered Xenon flash lamp having a spectrum close to a AM 1.5 light spectrum, as defined in the international standard IEC 60904-3.

5. Method according to any one of claims 1 to 4, characterized in that said at least two narrow band width light sources comprise light emitting diodes or light emitting diode arrays, the emitted light of said second light source being predominately absorbed in a first junction and the emitted light of said third light source being predominately absorbed in a second junction of the tandem solar cell under test.

6. Method according to any one of claims 1 to 5, wherein the absolute and relative light intensities of the light sources are measured and/or controlled by optically filtered PV monitor cells that are only sensitive to the spectrum of the light source to be monitored.

7. Method according to any one of claims 1 to 6, wherein additional steps are performed that consist in calculating solar cell parameters chosen among: acquired IV curve as of the short circuit current, the open circuit voltage , the fill factor, the series resistance, the parallel resistance or a combination of them.

8. Method according to any of claims 1 to 7 wherein the time to characterize a tandem solar cell is performed in less than 1 min, preferably less than 10 seconds, more preferably less than 5 seconds, even more preferably less than 0.15 seconds.

9. A solar cell test apparatus for characterizing, carrying out the method of any one of claims 1 to 8, a tandem solar cell comprising at least two sub-cells, the apparatus comprising at least one first light source for providing a light beam that has a spectrum corresponding to the international standard AM1.5 and wherein the test apparatus comprises further at least two narrow bandwidth light

sources, for providing at least two different light beams, each light beam being predominately absorbed by one of the at least two sub-cells.

10. The solar cell test apparatus according to claim 9 comprising more than 2 different narrow band light sources $S2_N$, N possibly being at least 4, possibly at least 5, even more possibly at least 6.

11. The solar cell test apparatus according to claim 9 or claim 10 wherein the first light source is a filtered Xenon flash lamp having a spectrum close to an AM 1.5 light spectrum, as defined in the international standard IEC 60904-3.

12. The solar cell test apparatus according to any one of claims 9 to 11 wherein at least one of said narrow band light sources is a light emitting diode (LED).

13. The solar cell test apparatus according to any one of claims 9 to 12, comprising at least one light intensity monitoring devices.

14. The solar cell test apparatus according to claim 13, wherein said light intensity monitoring device is a photovoltaic silicon diode.

15. The solar cell test apparatus according to claim 14, wherein said light intensity monitoring device comprises at least one optical band-pass filter.