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(54) Title: METHOD AND APPARATUS FOR CHARACTERIZATION OF A SOLAR CELL

(57) Abstract: The present disclosure relates to a method for characterization of a solar cell, comprising the steps of: providing an optical probe light; modulating the optical probe light with a modulation frequency of between 100 kHz and 50 MHz, thereby obtaining a modulated probe light; scanning the modulated probe light such that said modulated probe light is incident on at least a part of the surface of the solar cell, and such that the part of the solar cell exposed to the modulated probe light converts the modulated probe light to an electrical signal; detecting and analyzing said electrical signal; and estimating variations in the solar cell, thereby electrically characterizing the solar cell. The disclosure further relates to a solar cell characterization apparatus for characterization of a solar cell, comprising: a light source for generating an optical probe light; a modulation unit, configured to produce modulated probe light by modulating the optical probe light with a modulation frequency of between 100 kHz and 0 MHz; a light scanning unit for scanning the modulated probe light such that said modulated probe light is incident on at least a part of the surface of the solar cell; and a 1 signal analyzer, configured to detect and analyze electrical signals produced by the solar cell as a response to exposure of the modulated probe light.

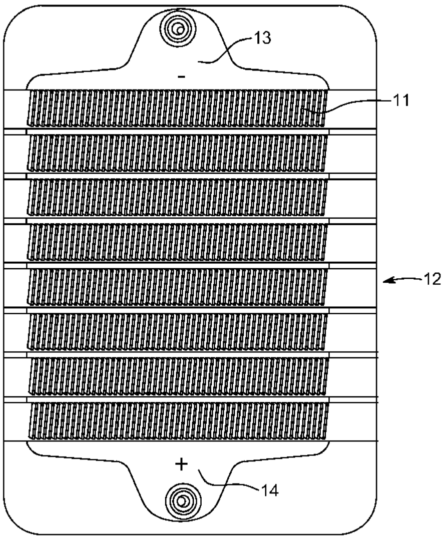

FIG. 3

Method and apparatus for characterization of a solar cell

The present disclosure relates to a method for characterization (i.e. estimating variations) of a solar cell. The disclosure further relates to an apparatus capable of characterizing a solar cell.

Background of invention

Materials used to manufacture solar cells may contain defects, which can impact the electrical performance of solar cells negatively. Defects can also be generated during the manufacturing of solar cells or during usage. Printed organic photovoltaic (OPV) solar cells are polymer-based thin film solar cell. OPV solar are lightweight, flexible, inexpensive, highly tuneable and potentially disposable.

Light beam induced current (LBIC) is a non-destructive technique that focuses light onto a solar cell, thereby creating a photo-generated current that can be measured as a function of its position on the cell surface. LBIC is a well-established 2D mapping technique for characterization of solar cells. By measuring the variation in the generated current, the areas corresponding to lower performance can be identified. The measured current values for each point are translated into a scale of different color hues representing level of performance. LBIC mapping is especially relevant for roll-to-roll (R2R) printed OPV solar cells. This type of photovoltaics is printed/coated on plastic substrates layer by layer which inevitably generates many types of defects such as layer thickness variations, misalignment, dewetting spots, delamination, particle contamination etc. Most of these defects are fairly benign giving rise to less performing areas whereas others are more serious creating electrical shorts that may even shunt a whole cell or create an open circuit in the defect area.

A major limitation of the LBIC technique is the time it takes to perform a characterization. The light beam has to be repositioned to a number of spots/pixels to cover the whole area to characterize and record the current measured on each spot/pixel accordingly. As an example, for a 10 cm^2 area image at 100 µm resolution this means investigating 10^6 points. At a measuring speed of 100 ms per point this means a total of over 24 hours to complete the characterization. It appears that conventional LBIC has severe limitations for testing/manufacturing purposes.

Moreover, the light beam in LBIC may be affected by stray light or changes in background light, which can degrade the precision of the characterization. On a more general level, the induced current is affected by noise from various sources, e.g. electrical noise, static charges, contact resistance etc. In particular if the signal is weak, the signal to noise ratio (SNR) is typically consequently low, resulting in poor characterization of the solar cell.

Summary of invention

The present disclosure relates to heterodyne LBIC i.e. a method for characterization of a solar cell, comprising the steps of: providing an optical probe light; modulating the optical probe light with a modulation frequency of between 100 kHz and 50 Mhz, thereby obtaining a modulated probe light; scanning the modulated probe light such that said modulated probe light is incident on at least a part of the surface of the solar cell, and such that the part of the solar cell exposed to the modulated probe light converts the modulated probe light to an electrical signal; and detecting and analyzing said electrical signal. The electrical signal may then be used for estimating variations in the solar cell, thereby electrically characterizing the solar cell. By modulating the optical probe light with a modulation frequency of between 100 kHz and 50 MHz, preferably in the range of 1 MHz-10MHz, the method can be said to introduce technology in LBIC that is more typically used in radio transmission applications. In this regard, the optical probe light may be viewed as a carrier signal or carrier wave with an optical frequency capable of inducing a photovoltaic effect. The modulated probe light is converted to an electrical signal. Preferably the electrical signal comprises the modulation frequency of between 100 kHz and 50 MHz. The modulation of the electrical signal is preferably substantially the same or similar as the modulation frequency but not in the same range as the frequency of the optical probe light. Therefore, the invention can be said to make use of the additional information that is carried by the modulated signal. Modulating the optical probe light with a modulation frequency of between 100 kHz and 50 MHz and sweeping the modulated signal over the surface provides a way of performing LBIC much faster than traditional LBIC. Heterodyning is a radio signal processing technique in which new frequencies are created by combining or mixing two frequencies into a new signal. Superheterodyne refers to heterodyning of supersonic signals. Therefore, in one embodiment, the presently disclosed method can be considered to operate on radio frequency (RF) signals rather than only the optical probe light. The method also enables for measurement using many different modulation frequencies and/or wavelengths, which increases the capacity of the analysis.

Modulating the optical probe light, which typically comprises one or several laser beams, with an RF signal for LBIC purposes presents a number of advantages compared to traditional LBIC (in which light is focused on one pixel, the current measured, the light source then moved to another pixel and so forth). Since the modulated probe light can be captured by the solar sell by using the solar cell as an antenna for RF signals, the signal can be analyzed in the frequency domain, for example by means of a spectrum analyzer. This is a new way of performing LBIC, which is significantly faster than traditional LBIC. By scanning the modulated probe light over the surface of the solar cell and analyze the RF modulated signal in the frequency domain (alternatively, the detected modulated signal can be oversampled) significantly faster characterization can be achieved. The invention can be said to take advantage of the additional information that is carried by the modulated signal. In one embodiment the modulated probe light is scanned over the surface of the solar cell by means of a rotating polygonal mirror, which allows for continuous sweeping rather than stopping and repositioning of the beam. The combination of modulating the optical probe light with a modulation frequency of at least 100 kHz and sweeping the modulated signal over the surface of the solar cell provides a very efficient way of performing fast LBIC, in particular in combination with analysis of the detected signal in the frequency domain, possibly involving the step of Fourier-transforming the electrical signal. Moreover, the method enables for measurement using many different modulation frequencies and/or wavelengths, which increases the capacity of the analysis.

As stated the presently disclosed method is significantly faster than traditional LBIC. However, it also has other advantages. The modulated probe light is not sensitive to stray light in the same way as traditional LBIC and the signal is also generally less sensitive to noise. The modulation frequency can be distributed over a bandwidth, e.g. having a frequency range of 800 Hz – 17 kHz. The pixel resolution of the solar cell that is characterized is determined by the acquisition bandwidth and center frequency. Hence, the method also provides flexibility in terms of resolution versus speed of the characterization. Furthermore, increased bandwidth can also be used to improve the performance of a characterization in scenarios involving weak electrical signal. Basically a weak signal is more likely to have a lower signal to noise (SNR) ratio. In radio communication bandwidth is the frequency range occupied by a modulated carrier wave. In relation to the presently disclosed method the bandwidth can be decreased to compensate for a weak signal with a compromise on resolution.

The present disclosure further relates to a solar cell characterization apparatus for characterization of a solar cell, comprising: a light source for generating an optical probe light; a modulation unit, configured to produce modulated probe light by modulating the optical probe light with a modulation frequency of at least 100 kHz; a light scanning unit for scanning the modulated probe light such that said modulated probe light is incident on at least a part of the surface of the solar cell; and a signal analyzer, configured to detect and analyze electrical signals produced by the solar cell as a response to exposure of the modulated probe light. The signal analyzer is, in a preferred embodiment, an RF spectrum analyzer. The present disclosure further relates to an apparatus as described above using the method of the presently disclosed invention.

These and other aspects of the invention are set forth in the following detailed description if the invention.

Description of drawings

Fig. 1 is a schematic drawing of one embodiment of the presently disclosed LBIC setup for characterization of a solar cell.

Fig. 2 shows another embodiment of an apparatus for characterization of a solar cell, operating on a module comprising a plurality of solar cells and a plurality of probe lights.

Fig. 3 shows an example of an organic solar cell.

Fig. 4 shows an example of LBIC mapping performed with the presently disclosed method for characterization of a solar cell.

Fig. 5 shows an example of an established LBIC signal corresponding to a modulated probe light sweeping over 8 solar cells.

Detailed description of the invention

The present disclosure relates to heterodyne LBIC i.e. a method for characterization of a solar cell, comprising the steps of: providing an optical probe light; modulating the optical probe light with a modulation frequency of at least 100 kHz, thereby obtaining a modulated probe light; scanning the modulated probe light such that said modulated probe light is incident on at least a part of the surface of the solar cell, and such that the part of the solar cell exposed to the modulated probe light converts the modulated probe light to an electrical signal; and detecting and analyzing said electrical signal. The electrical signal may then be used for estimating variations in the solar cell, thereby electrically characterizing the solar cell. By modulating the optical probe light with a modulation frequency of at least 100 kHz, preferably in the range of 1 MHz-10MHz, the method can be said to introduce technology in LBIC that is more typically used in radio transmission applications. Traditional LBIC involves moving a focused light source, typically a laser over the solar cell while measuring the current output directly. The presently disclosed method enables the analysis of the received modulated probe light, or rather the converted electrical signal, in the frequency domain. The inventor has realized that the concept of heterodyning can be applied on LBIC by modulating the optical probe light with a modulation frequency operating in a radio frequency range. There are a number of potential defects in solar cells e.g. layer thickness, misalignment of the cells, dewetting spots and/or delamination and/or particle contamination. In one embodiment of the presently disclosed method for characterization of a solar cell, physical variations in the solar cell are estimated as the ability to absorb power of the modulated probe light. As stated LBIC mapping is especially relevant for OPV solar cells, which often have defects which are benign giving rise to less performing areas whereas others are more serious creating electrical shorts that may even shunt a whole cell or create an open circuit in the defect area. The presently disclosed method for performing characterization of a solar cell is significantly faster than traditional LBIC since it by modulating the probe light, preferably distributed over a bandwidth of 800 Hz - 17 kHz, and analyzing in the frequency domain can be said to carry additional information compared to an unmodulated signal. The method turns out to be beneficial for manufacturing tests of solar cells and in particular roll-to-roll manufacturing of OPV, including tandem solar cells.

The solar cell can be said to act as an antenna capturing the RF signals. In principle the presently disclosed method allows for optical probe light modulated with a modulation frequency between many frequencies and bandwidths. The higher the modulation frequency, the higher the amount of data included in the signal. In one embodiment of the presently disclosed method for characterization of a solar cell the optical probe light is therefore modulated with a modulation frequency between 100 kHz and 50 MHz, or between 100 kHz and 30 MHz, or between 500 kHz and 30 MHz, or between 100 kHz and 10 MHz, or between 500 kHz and 30 MHz, or between 1 MHz and 10 MHz. Also, by using a range of frequencies increases the amount of carried data. Therefore, in one embodiment of the presently disclosed method for characterization of a solar cell, the optical probe light is modulated with a modulation frequency distributed over a bandwidth of 100 kHz – 10 MHz, or a bandwidth of 100 kHz - 1 MHz, or a bandwidth of 800 Hz - 17 kHz, or a bandwidth of 100 Hz - 400 kHz, or a bandwidth of 200 Hz - 800 kHz, or a bandwidth of 400 Hz - 2 kHz, or a bandwidth of 400 Hz - 5 kHz, or a bandwidth of 400 Hz - 10 kHz. Lower bandwidth can be also used to compensate for a weak signal. A weak signal typically has a lower SNR ratio. In radio communication bandwidth is the frequency range occupied by a modulated carrier wave. By increasing the bandwidth two effects can be achieved. Generally, the signal carries more data, and the wider frequency range opens for more extensive filtering of undesired frequencies while maintaining relevant transmitted data in the signal.The modulation of the optical probe light with a modulation frequency of at least 100 kHz is typically performed by means of a local oscillator and a mixer as can be seen in e.g. fig. 1. The modulated wave may be a complex wave and/or may be described as an oscillating wave having an amplitude A, a frequency f and a phase φ.

The received modulated signal can then be analyzed by a signal analyzer, preferably including a spectrum analyzer. Examples of suitable signal analyzers are the Agilent MX/PX series or the R&S FSW series. However, simpler and more low cost solutions may also be used.

In one embodiment of the presently disclosed method for characterization of a solar cell, the received modulated signal is Fourier-transformed. A common problem in reconstruction transmitted data is noise. Noise can corrupt a signal e.g. by measurement issues, sampling time, sensor bias etc. One way of filtering data is using a Fourier transform, which can be said to decompose a function of time into the frequencies that make it up, similarly to how a musical chord can be expressed as the amplitude (or loudness) of its constituent notes. The Fourier transform is sometimes referred to as the frequency domain representation of the original signal. In the presently disclosed method for characterization of a solar cell, the Fourier transformation may be used e.g. to filter noise.

As an alternative to analyzing the received signal in the frequency domain, the signal can be oversampled by the analyzer. In signal processing oversampling is usually referred to as the process of sampling with a sampling frequency higher than the Nyquist rate. Theoretically a bandwidth-limited signal can be perfectly reconstructed if sampled above the Nyquist rate, which is twice the highest frequency in the signal. By oversampling the received modulated signal in the presently disclosed method all the information can be extracted from the signal.

A radio receiver is an electronic device that receives radio waves and converts the information carried by them to a usable form. It is used with an antenna. The antenna intercepts electromagnetic waves and converts them to alternating currents which are applied to the receiver and the receiver extracts the desired information. In the present invention a radio receiver or signal analyzer is preferably used to extract the modulated frequency from the transmitted modulated light probe light through demodulation, wherein the solar cell acts as antenna.

In one embodiment of the presently disclosed method for characterization of a solar cell, a galvo motor is used in combination with a mirror for scanning the modulated probe light. Galvo motors are limited-rotation DC motors that drive mirrors for laser-beam steering or scanning applications. Controlled motion can be achieved by means of an internal position detector that enables closed loop servo control of the motor. In a further embodiment, a rotatable polygonal mirror is used for scanning the modulated probe light across the solar cell or across a number of solar cells constituting a module. A major advantage of this solution is the substantially constant scan velocity that repeats itself for every segment of the polygonal mirror when the mirror rotates. The term module refers to an assembly of solar cells – solar cells can be said to be the building blocks of photovoltaic modules. The solar cells are typically connected in series. The present method is inherently suited for analysis of modules of solar cells, and the combination of a polygonal mirror and the presently disclosed method is particularly useful for achieving fast, precise and flexible characterization of modules.

In one embodiment the optical probe light of the presently disclosed method for characterization of a solar cell has a wavelength between 150 nm and 30 µm, or between 400 nm and 3 µm, or between 400 nm and 750 nm, or between 750 nm and 3 µm, or between 700 nm and 1500 nm, or between 700 and 1800 nm, or between 200 nm and 1200 nm, or between 400 nm and 1200 nm, such as 410 nm, or 405 nm, or 637 nm, or 785 nm, or 940 nm, or 1040 nm, or 1100 nm, or 1140 nm. The invention is suitable for a broad range of light source, preferably lasers such as ultraviolet laser and/or visible laser and/or near-infrared laser and/or mid-infrared laser, such as blue laser and/or green laser and/or red laser and/or red laser. The optical probe light may also comprise white light or any combination of lights of different wavelengths

An effective way of improving solar cell efficiency is to use a tandem structure, as a broader part of the spectrum of solar radiation is used and the thermalization loss of photon energy is minimized. Tandem cells are basically two solar cells with complementary absorption range. The presently disclosed method has proved to be an efficient way of characterizing tandem cells. In one embodiment of the presently disclosed method for characterization of a solar cell the optical probe light comprises at least two different light beams, preferably focused on the same pixel. The at least two light beams preferably have different wavelengths but could also be the same. One aspect of the present method relates to the at least two probe lights being modulated with different frequencies. In this way the probe lights for the two junctions of the tandem cell operate not only with different wavelengths but also with different modulation radio frequencies, which can be used in the analysis stage for more clearly distinguishing the different junctions. More generally, the present disclosure relates to the generalization of the concept to cover additional beams, modulation frequencies and multijunction solar cells. Also the phase φ of the modulated signal may be used as a means to maintain a difference of the signals to analyze for the junctions. Thus, the method can said to be inherently suited for analysis of multijunction solar cells.

The present disclosure further relates to a solar cell characterization apparatus for characterization of a solar cell, comprising: a light source for generating an optical probe light; a modulation unit, configured to produce modulated probe light by modulating the optical probe light with a modulation frequency of at least 100 kHz; a light scanning unit for scanning the modulated probe light such that said modulated probe light is incident on at least a part of the surface of the solar cell; and a signal analyzer, configured to detect and analyze electrical signals produced by the solar cell as a response to exposure of the modulated probe light. Typically the apparatus comprises a local oscillator configured to generate the signal with which the probe light is modulated. Preferably the signal analyzer is configured to analyze the electrical signals in the frequency domain as described above i.e. including noise filtering, possibly including using a Fourier transform etc., or, as an alternative, means for oversampling the received signal. The signal analyzer may be e.g. a spectrum analyzer, signal analyzers such as the Agilent MX/PX series or the R&S FSW series, or simpler and cheaper solutions that are capable of analyzing the received signals, preferably in the frequency domain.

In one embodiment of the apparatus, the local oscillator/signal generator is an RF signal generator and/or a signal generator configured to generate a modulation signal having a frequency between 100 kHz and 50 MHz, or between 100 kHz and 30 MHz, or between 500 kHz and 30 MHz, or between 100 kHz and 10 MHz, or between 500 kHz and 30 MHz, or between 1 MHz and 10 MHz The local oscillator and mixer may be included in one circuit. Therefore, in one embodiment of the presently disclosed apparatus, the modulation unit comprises a mixing unit configured to mix the modulation signal with the optical probe light. The light source for generating an optical probe light is preferably a laser configured to generate a laser beam.

Different configurations for scanning the modulated probe light can be imagined. Most laser scanners use moveable mirrors to steer the laser beam. The steering of the beam can be one-dimensional or two-dimensional. Additionally, the mirrors can lead to a periodic motion, such as for rotating mirror polygons, galvanometer scanners or servo-controlled galvanometer scanners or vector scanner. The purpose of a rotating mirror is to scan the modulated probe light across at least a part of the solar cell, and the position of the mirror determines the position of the modulated probe light on the solar cell. When the mirror rotates, the light beam sweeps over the solar cell or module of solar cells, preferably with a substantially constant scan velocity. If the mirror is a polygonal mirror, the sweeping repeats itself for every segment of the polygonal mirror.

In one embodiment of the apparatus, the signal analyzer is connected to the solar cell through contactless capacitive coupling. This type of connection is especially suited for fast roll-to-roll characterization of OPV. As an alternative the signal can be transferred by means of inductive coupling. Physical electrical contacts may be inconvenient for the process of e.g. roll-to-roll LBIC and therefore contactless LBIC constitutes an efficient way of transferring the captured signals to the signal analyzer.

Detailed description of drawings

Fig. 1 shows one embodiment of the presently disclosed LBIC setup for characterization of a solar cell. A light source 5, preferably a laser, generates an optical probe light 1, which is modulated in a modulation unit 6. Conceptually, the modulation is illustrated as the modulation unit 6 receiving the optical probe light and a modulation signal from a local oscillator 8, and generating a modulated probe light 3. The modulated probe light 3 is scanned such that it is incident on the surface of a solar cell 11. In this setup a rotating polygonal mirror 10 is used for scanning the modulated probe light 3. In a simple setup, the detection and analysis of the received modulated signal is illustrated by positive and negative electrodes 14 and 13 connected to a signal analyzer 15, configured to detect and analyze electrical signals produced by the solar cell as a response to exposure of the modulated probe light. This signal analyzer 15 may comprise e.g. a radio frequency signal analyzer.

Fig. 2 shows a similar setup where two modulated lights are combined into one combined modulated probe light 21. A first optical probe light 1 having a wavelength λ_1 is modulated in a first modulation unit 6, thereby generating a first modulated probe light 3. A second optical probe light 2 having a wavelength λ_2 is modulated in a second modulation unit 7, thereby generating a second modulated probe light 4. These units may be included in a common unit, configured to perform all of the mentioned steps. The first modulated probe light 3 and second modulated probe light 4 are then combined intro a combined modulated probe light 21. Both wavelength and modulation frequencies may be freely chosen, i.e. may be the same or different for the two modulated probe lights. Having more than one probe light as illustrated in this setup is particularly useful for tandem or multijunction solar cells. A setup using four probe lights with four different wavelengths has been demonstrated. In the example shown in fig. 2, several solar cells 11 are serially connected to form a module 12 comprising a plurality of solar cells. A rotating polygonal mirror 10 is used for scanning the combined modulated probe light 21 over the surface of the module 12. The measurement of received signals may be achieved involving contactless coupling, illustrated by positive and negative electrodes 14 and 13 and an inductive coupling 16. The analysis part of the receive signal includes means for analyzing the received signal as a complex waveform (IQ) 17, filtering any part of the spectrum 18, and a signal analyzer 15. These means for analyzing the received signal may form an integral unit.

Fig. 3 shows a module 12 of solar cells 11. The solar cells 11 are serially connected to form a module 12 comprising a plurality of solar cells. The solar cell module has a positive electrode 14 and a negative electrode 13.

Fig. 4 shows an example of LBIC mapping performed with the presently disclosed method for characterization of a solar cell. It shall be noted that 11 and 12 do not refer to a solar cell (11) and module of solar cells (12) directly – fig. 4 is an actual resulting picture of the characterization according to the presently disclosed method and not a direct photo or depicture of the module of solar cells. The less performing areas 19 are results of areas within the module of solar cells associated with defects on the solar cells.

Fig. 5 shows an example of an established LBIC signal corresponding to a modulated probe light sweeping over 8 solar cells using the presently disclosed method for characterization of a solar cell. The diagram does not show the identification of the modulation frequency performed by a spectrum analyzer.

Further details of the invention

1. A method for characterization of a solar cell, comprising the steps of:
    - providing an optical probe light;
    - modulating the optical probe light with a modulation frequency of at least 100 kHz, thereby obtaining a modulated probe light;
    - scanning the modulated probe light such that said modulated probe light is incident on at least a part of the surface of the solar cell, and such that the part of the solar cell exposed to the modulated probe light converts the modulated probe light to an electrical signal;
    - detecting and analyzing said electrical signal; and
    - estimating variations in the solar cell, thereby electrically characterizing the solar cell.

2. The method according to any of the preceding items, wherein the electrical signal is analyzed in the frequency domain.

3. The method according to any of the preceding items, wherein the electrical signal is Fourier-transformed.

4. The method according to any of the preceding items, wherein the modulation frequency is between 100 kHz and 50 MHz.

5. The method according to any of the preceding items, said optical probe light acting as a carrier wave.

6. The method according to item 5, wherein the optical probe induces a photovoltaic effect.

7. The method according to any of the preceding items, wherein the electrical signal comprises the modulation frequency of between 100 kHz and 50 MHz.

8. The method according to any of the preceding items, wherein the electrical signal is oversampled.

9. The method according to any of the preceding items, said optical probe light having a wavelength between 150 nm and 30 µm, preferably between 400 nm and 3 µm, more preferably between 400 nm and 750 nm, even more preferably between 750 nm and 3 µm, most preferably between 700 nm and 1500 nm, such as 410 nm, or 405 nm, or 637 nm, or 785 nm, or 940 nm, or 1040 nm, or 1100 nm, or 1140 nm.

10. The method according to any of the preceding items, said optical probe light comprising a combination of lights of different wavelengths.

11. The method according to any of the preceding items, said optical probe light comprising at least two different light beams having different wavelengths, or at least three different light beams having different wavelengths.

12. The method according to any of the preceding items, said optical probe light comprising white light.

13. The method according to any of the preceding items, said optical probe light comprising at least one laser beam.

14. The method according to item 13, wherein the laser beam(s) comprise(s) ultraviolet laser and/or visible laser and/or near-infrared laser and/or mid-infrared laser, such as blue laser and/or green laser and/or red laser and/or red laser.

15. The method according to any of the preceding items, wherein the optical probe light is modulated with a plurality of modulation frequencies.

16. The method according to any of the preceding items, said optical probe light comprising at least two different light beams, said at least two different light beams modulated with different frequencies.

17. The method according to any of the preceding items, wherein the optical probe light is modulated with a modulation frequency between 100 kHz and 30 MHz, preferably between 500 kHz and 30 MHz, more preferably between 100 kHz and 10 MHz, even more preferably between 500 kHz and 30 MHz, most preferably between 1 MHz and 10 MHz.

18. The method according to any of the preceding items, wherein the optical probe light is modulated with a modulation frequency distributed over a bandwidth of 100 kHz – 10 MHz, preferably a bandwidth of 100 kHz - 1 MHz, more preferably a bandwidth of 800 Hz - 17 kHz, even more preferably a bandwidth of 100 Hz - 400 kHz, even more preferably a bandwidth of 200 Hz - 800 kHz, even more preferably a bandwidth of 400 Hz - 2 kHz, even more preferably a bandwidth of 400 Hz - 5 kHz, most preferably a bandwidth of 400 Hz - 10 kHz.

19. The method according to any of the preceding items, said electrical signal comprising at least one frequency determined by the modulation frequency.

20. The method according to any of the preceding items, wherein the electrical signal is recovered and/or captured by using the solar cell as antenna.

21. The method according to any of the preceding items, wherein physical variations in the solar cell are estimated as the ability to absorb power of the modulated probe light.

22. The method according to any of items 20-21, wherein the recovered signal is a radio frequency signal.

23. The method according to item 22, wherein the recovered signal is treated as a complex waveform.

24. The method according to any of the preceding items, wherein the electrical signal is analyzed in the frequency domain by means of a signal analyzer and/or a spectrum analyzer.

25. The method according to any of the preceding items, wherein the step of modulating the optical probe light with a modulation comprises heterodyning.

26. The method according to any of the preceding items, wherein the step of modulating the optical probe light with a modulation comprises superheterodyning.

27. The method according to any of the preceding items, wherein the scanning of the modulated probe light is performed by a rotating mirror, such as a rotating polygonal mirror.

28. The method according to any of the preceding items, wherein the estimated variations in the solar cell correspond to layer thickness and/or misalignment of the cells and/or dewetting spots and/or delamination and/or particle contamination.

29. A solar cell characterization apparatus for characterization of a solar cell, comprising:
    - a light source for generating an optical probe light;
    - a modulation unit, configured to produce modulated probe light by modulating the optical probe light with a modulation frequency of at least 100 kHz;

- a light scanning unit for scanning the modulated probe light such that said modulated probe light is incident on at least a part of the surface of the solar cell; and
- a signal analyzer, configured to detect and analyze electrical signals produced by the solar cell as a response to exposure of the modulated probe light.

30. The apparatus according to item 29, wherein the signal analyzer is configured to analyze the electrical signals in the frequency domain.

31. The apparatus according to any of items 29-30, wherein the light source is a laser configured to generate a laser beam.

32. The apparatus according to any of items 29-31, said modulation unit comprising a signal generator configured to generate a modulation signal having a frequency between 100 kHz and 50 MHz, preferably between 100 kHz and 30 MHz, more preferably between 500 kHz and 30 MHz, even more preferably between 100 kHz and 10 MHz, even more preferably between 500 kHz and 30 MHz, most preferably between 1 MHz and 10 MHz.

33. The apparatus according to item 32, wherein the signal generator is a radio frequency signal generator.

34. The apparatus according to any of items 29-33, said modulation unit comprising a mixing unit configured to mix the modulation signal with the optical probe light.

35. The apparatus according to any of items 29-34, wherein the light scanning unit is a laser scanner and/or a mirror configured for scanning the modulated probe light across at least a part of the solar cell.

36. The apparatus according to any of items 29-35, wherein the light scanning unit is a rotatable polygonal mirror.

37. The apparatus according to any of items 29-36, wherein the position of the light source is fixed and the scanning unit determines the position of the modulated probe light on the solar cell.

38. The apparatus according to any of items 29-36, wherein the signal analyzer is a spectrum analyzer.

39. The apparatus according to any of items 29-38, wherein the signal analyzer is a radio frequency signal analyzer.

40. The apparatus according to any of items 29-39, wherein the signal analyzer is connected to the solar cell through a physical electric contact or through contactless capacitive coupling.

41. Apparatus according to any of items 29-40 using the method according to any of items 1-28.

Claims

1. A method for characterization of a solar cell, comprising the steps of:
    - providing an optical probe light;
    - modulating the optical probe light with a modulation frequency of between 100 kHz and 50 MHz, thereby obtaining a modulated probe light;
    - scanning the modulated probe light such that said modulated probe light is incident on at least a part of the surface of the solar cell, and such that the part of the solar cell exposed to the modulated probe light converts the modulated probe light to an electrical signal;
    - detecting and analyzing said electrical signal; and
    - estimating variations in the solar cell, thereby electrically characterizing the solar cell.

2. The method according to any of the preceding claims, wherein the electrical signal is analyzed in the frequency domain.

3. The method according to any of the preceding claims, wherein the electrical signal is Fourier-transformed.

4. The method according to any of the preceding claims, said optical probe light acting as a carrier wave.

5. The method according to claim 4, wherein the optical probe induces a photovoltaic effect.

6. The method according to any of claims 4-5, said optical probe light having a wavelength between 150 nm and 30 µm, preferably between 400 nm and 3 µm, more preferably between 400 nm and 750 nm, even more preferably between 750 nm and 3 µm, most preferably between 700 nm and 1500 nm, such as 410 nm, or 405 nm, or 637 nm, or 785 nm, or 940 nm, or 1040 nm, or 1100 nm, or 1140 nm.

7. The method according to any of the preceding claims, wherein the electrical signal comprises the modulation frequency of between 100 kHz and 50 MHz.

8. The method according to any of the preceding claims, said optical probe light comprising a combination of lights of different wavelengths.

9. The method according to any of the preceding claims, said optical probe light comprising at least two different light beams having different wavelengths, or at least three different light beams having different wavelengths.

10. The method according to any of the preceding claims, said optical probe light comprising at least one laser beam.

11. The method according to any of the preceding claims, wherein the optical probe light is modulated with a plurality of modulation frequencies.

12. The method according to any of the preceding claims, said optical probe light comprising at least two different light beams, said at least two different light beams modulated with different frequencies.

13. The method according to any of the preceding claims, said electrical signal comprising at least one frequency determined by the modulation frequency.

14. The method according to any of the preceding claims, wherein the electrical signal is recovered and/or captured by using the solar cell as antenna.

15. The method according to claim 14, wherein the recovered signal is a radio frequency signal.

16. The method according to claim 15, wherein the radio frequency signal comprises the modulation frequency.

17. The method according to any of the preceding claims, wherein the electrical signal is analyzed in the frequency domain by means of a signal analyzer and/or a spectrum analyzer.

18. The method according to any of the preceding claims, wherein the step of modulating the optical probe light with a modulation comprises heterodyning.

19. A solar cell characterization apparatus for characterization of a solar cell, comprising:
    - a light source for generating an optical probe light;
    - a modulation unit, configured to produce modulated probe light by modulating the optical probe light with a modulation frequency of between 100 kHz and 50 MHz;
    - a light scanning unit for scanning the modulated probe light such that said modulated probe light is incident on at least a part of the surface of the solar cell; and
    - a signal analyzer, configured to detect and analyze electrical signals produced by the solar cell as a response to exposure of the modulated probe light.

20. The apparatus according to claim 19, wherein the signal analyzer is a spectrum analyzer and/or a radio frequency signal analyzer.

21. The apparatus according to any of claims 19-20, configured for performing the method according to any of claims 1-18.

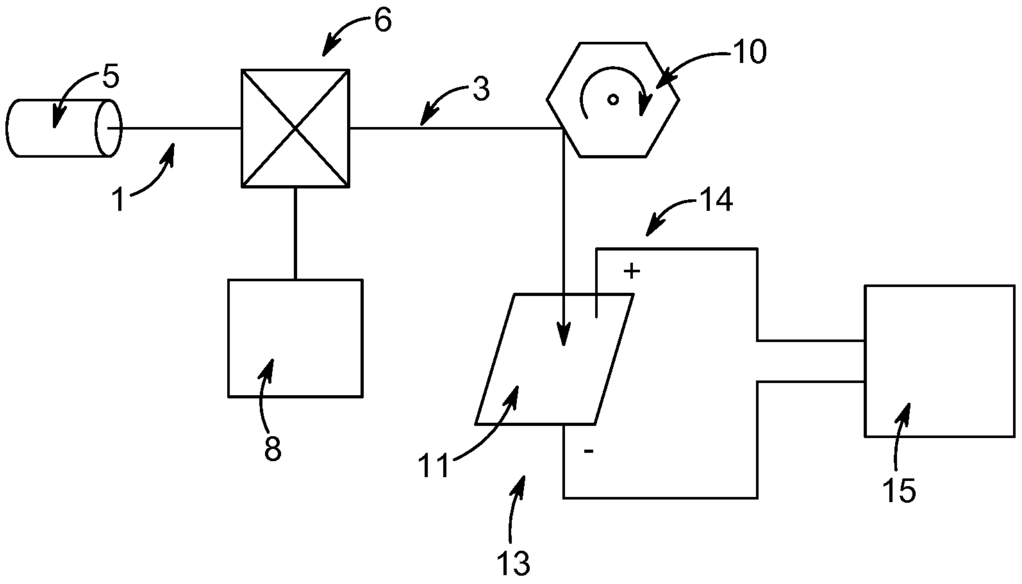
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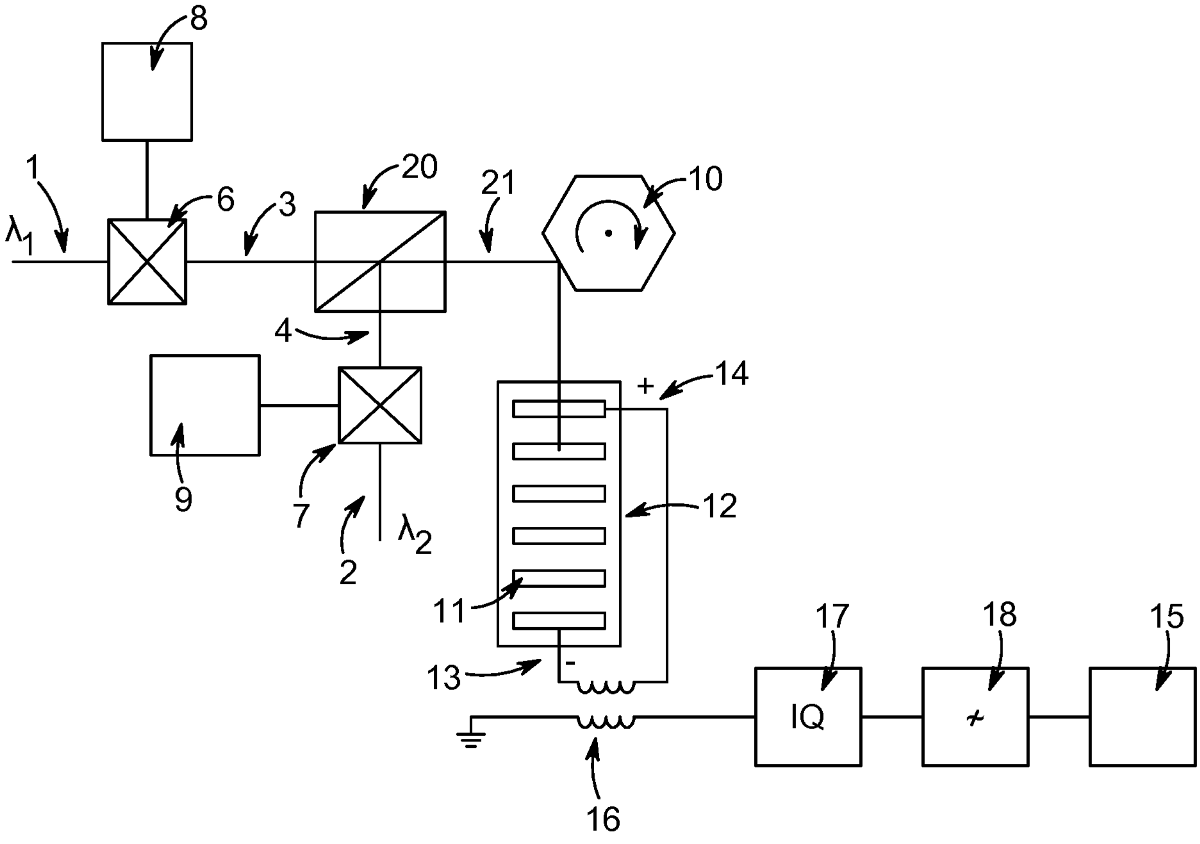
FIG. 1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20
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10
λ1
6
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λ2
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IQ
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FIG. 2

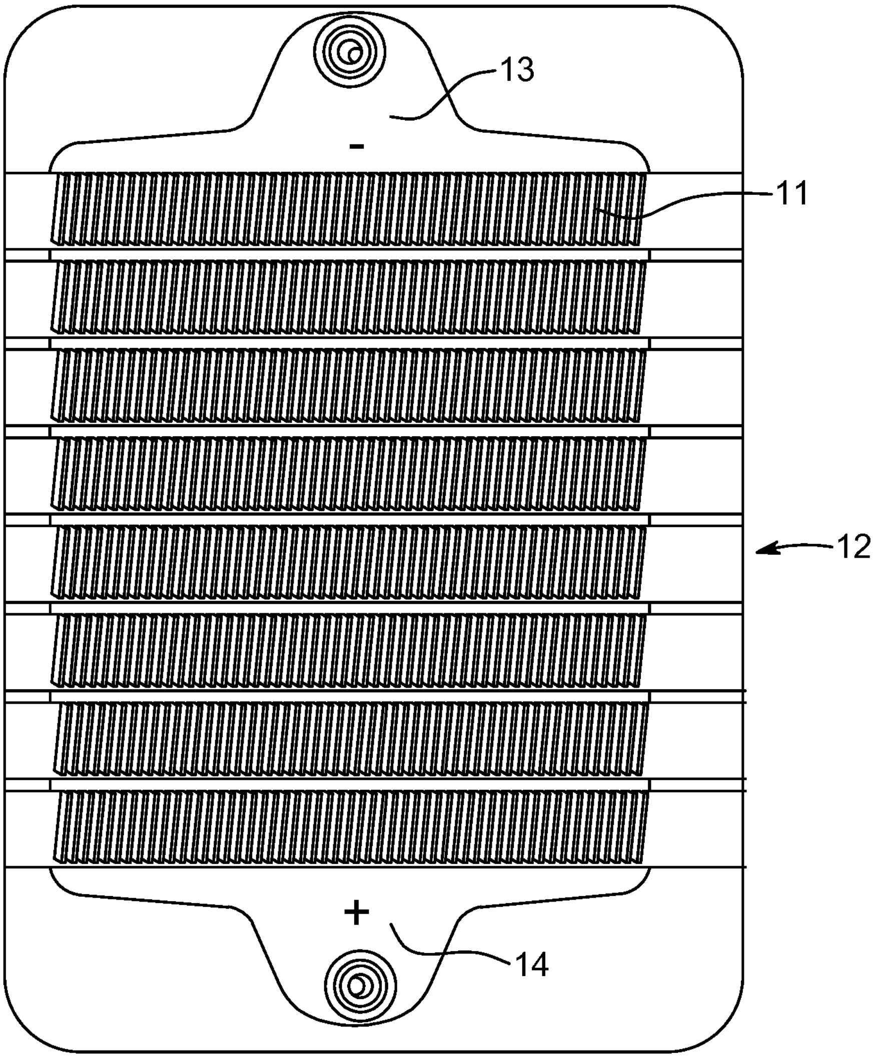

FIG. 3

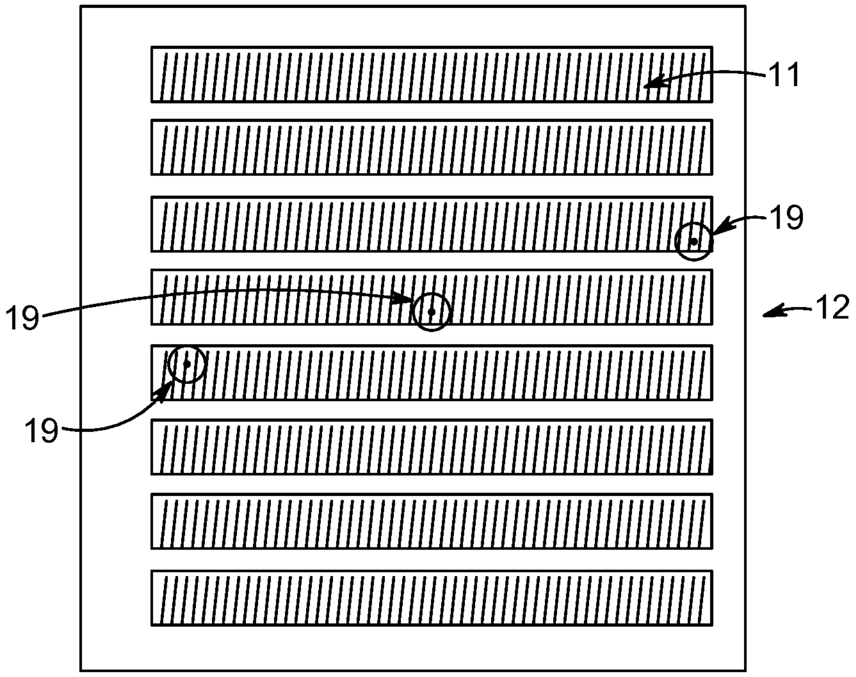

FIG. 4

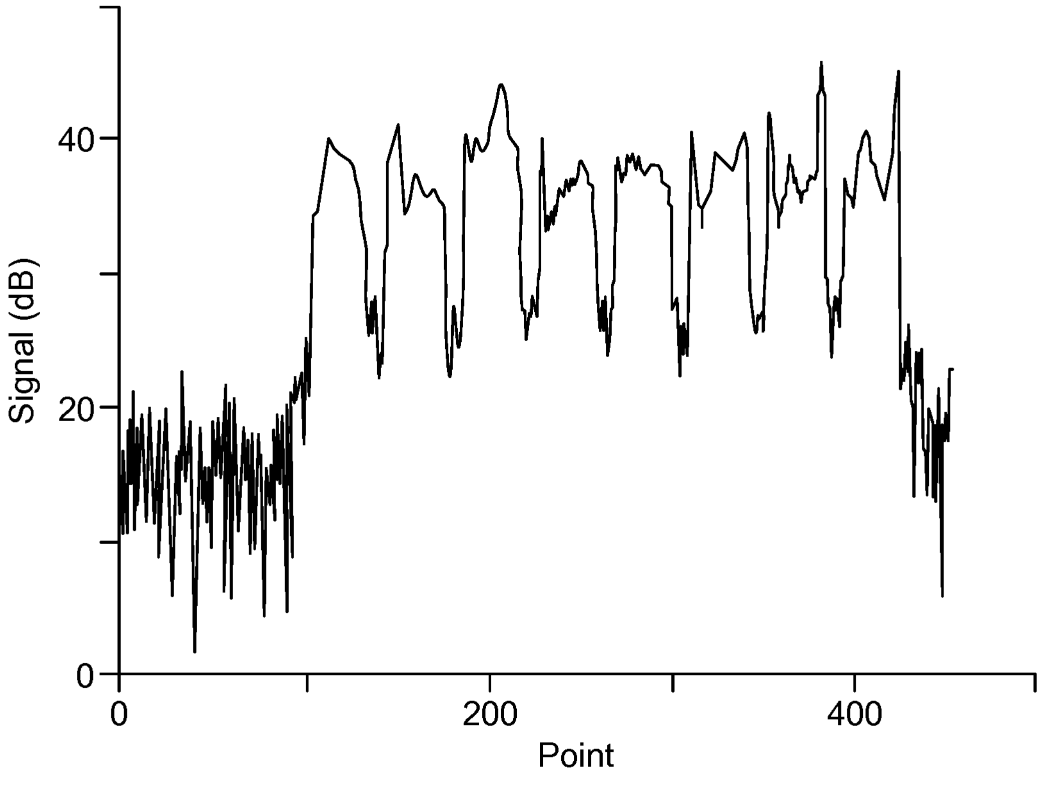

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/071133

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02S50/15
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H02S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2013/314118 A1 (MAK WING KEUNG [CN] ET AL) 28 November 2013 (2013-11-28) paragraphs [0048] - [0074]; figures 1-3b,6-7d -----	1-21
A	US 2015/015297 A1 (NAKANISHI HIDETOSHI [JP] ET AL) 15 January 2015 (2015-01-15) paragraphs [0050] - [0098]; figures 1-3 -----	1-21
A	DE 102 40 060 A1 (FRAUNHOFER GES FORSCHUNG [DE]) 25 March 2004 (2004-03-25) paragraphs [0027] - [0038]; figures 1,2 -----	1-15

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search 2 November 2016	Date of mailing of the international search report 08/11/2016
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Boero, Mauro

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2016/071133

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