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(54) Title: DEVICE CHARACTERISATION UTILISING SPATIALLY RESOLVED LUMINESCENCE IMAGING

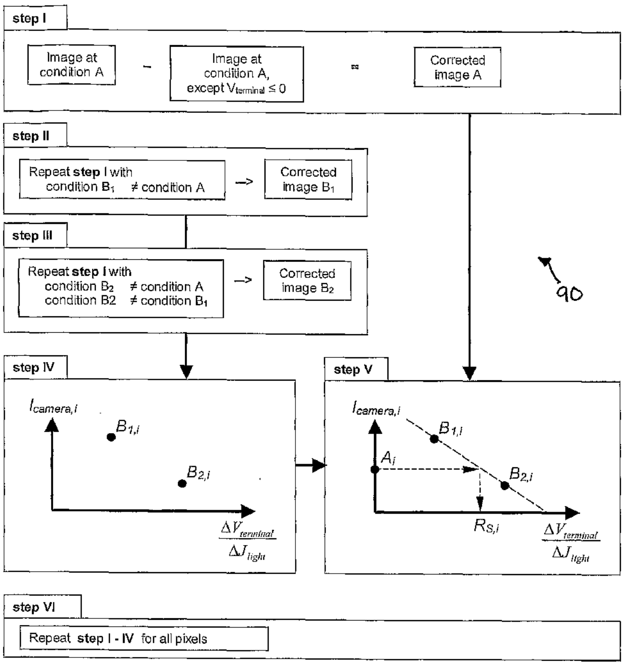

Fig. 9

(57) **Abstract**: A method for measuring the spatially resolved series resistance of a photovoltaic device using luminescence imaging. The method involves the steps of measuring a first luminescence intensity of an area of said device utilising an initial illumination intensity and terminal voltage, measuring a second luminescence intensity of said area of said device utilising a varied illumination intensity or varied terminal voltage, and measuring a third luminescence intensity of sai area in which at least one parameter is varied compared to measuring of said second luminescence intensity, said parameters being the terminal voltage and the illumination intensity. The second and third luminescence intensity values are extrapolated or interpolated to determine the values of terminal voltage and illumination intensity that would produce said First luminescence intensity, wherein the determined values are used to estimate the series resistance of said area of the device.

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Device Characterisation Utilising Spatially Resolved Luminescence Imaging

FIELD OF INVENTION

[001] The present invention relates broadly to characterisation of photovoltaic devices and in particular, to a non-destructive method of measuring the spatially resolved series resistance with low dependence on local diode characteristics.

BACKGROUND

[002] Optimisation and process control in volume production of solar cells requires the measurement of various electrical characteristics. Spatially resolved measurements across the area of an entire cell are especially attractive, allowing information regarding position-dependent variations of measured cell data to be obtained. This spatial information is crucial to track down problems such as inhomogeneous material quality, faulty or non-optimally configured manufacturing equipment or flaws in the layout design of the cell. For the purpose of process control in volume production of solar cells, characterisation methods should ideally be non-destructive and fast.

[003] Series resistance R_S is one of the major electrical characteristics of a solar cell, having a direct impact on cell efficiency. Series resistance often varies across the area of a solar cell, and knowledge of the local current density J_i at position i across a cell (or variations thereof (ΔJ_i)) is normally required for an accurate determination of the local series resistance $R_{S,i}$.

[004] In an illuminated solar cell J_i is given as: $J_i = J_{light} - J_{d,i}$, where J_{light} is the light-generated current which to a good approximation is linear in the illumination intensity, and $J_{d,i}$ is the local diode dark current density at position i. $J_{d,i}$ depends on the local diode voltage at position i (V_i) and on a number of other parameters, including the local diode saturation current and the local ideality factor, that vary across the area of a cell in a generally unknown manner.

[005] While some methods are known for measuring the spatially resolved series resistance across a solar cell, they all require measurement times of several minutes or even hours and/or are destructive. For example the contact resistance scanning ('Corescan') method (A.S.H. van der Heide *et al* Sol. Energy Mater. Sol. Cells 74 (2002) 43) requires a needle to be scratched through the passivation layer of a cell.

[006] Methods based on luminescence imaging have the potential to overcome the limitations of long measurement times and destructiveness. For example a method based on photoluminescence imaging has been reported by T. Trupke *et al* ('Spatially resolved series resistance of silicon solar cells obtained from luminescence imaging', Appl. Phys. Lett. 90 (2007) 093506), and methods based on electroluminescence imaging have been reported by D. Hinken *et al* ('Series resistance imaging of solar cells by voltage dependent electroluminescence', Appl. Phys. Lett. 91 (2007) 182104) and K. Ramspeck *et al* ('Recombination current and series resistance imaging of solar cells by combined luminescence and lock-in thermography', Appl. Phys. Lett. 90 (2007) 153502). A fundamental problem with these methods is the use of a global estimate for the unknown local diode properties, which leads to inaccuracies because the local diode properties (e.g. $J_{d,i}$) are in general not uniform but rather vary substantially across the device area.

[007] Any discussion of the prior art throughout the specification should in no way be considered as an admission that such prior art is widely known or forms part of common general knowledge in the field.

SUMMARY OF THE INVENTION

[008] It is an object of the present invention in its preferred form to provide a method for estimating spatially resolved series resistance data.

[009] In accordance with a first aspect of the present invention, there is provided a method of estimating the series resistance at an area of a diode device, the method comprising the steps of: measuring a first luminescence intensity A of the area of the device utilising an initial illumination intensity and terminal voltage; measuring a second luminescence intensity B_1 of the area utilising a varied illumination intensity or varied terminal voltage; measuring a third luminescence intensity B_2 of the area in which at least one parameter is varied compared to the measuring of the second corrected luminescence intensity B_1, the parameters being the terminal voltage and the illumination intensity; interpolating or extrapolating the luminescence intensity values from the second B_1 and third B_2 luminescence intensities to determine the values of the parameters that would produce the first luminescence intensity A; and using the determined parameter values to estimate the series resistance at the area.

[0010] Preferably, the area corresponds to one or more pixels of a luminescence image. In some embodiments, at least one luminescence intensity is generated with zero illumination intensity. Preferably, if a luminescence intensity is generated with non-zero illumination intensity, that luminescence intensity is corrected for the diffusion limited minority carrier lifetime of the material comprising the device by determining a reverse biased or zero bias condition of minimum luminescence intensity of the area.

[0011] In some embodiments, the illumination intensity is varied between the first luminescence intensity measurement A and the second luminescence intensity measurement B_1, and the terminal voltage is held substantially constant. Preferably, in some embodiments, the terminal voltage is varied between the first luminescence intensity measurement A and the second luminescence intensity measurement B_1, and the illumination intensity is held substantially constant. In some embodiments, the terminal voltage is varied between the second B_1 and third B_2 luminescence intensity measurements and the illumination intensity is held substantially constant. In other embodiments, the illumination intensity is varied between the second B_1 and third B_2 luminescence intensity measurements and the terminal voltage is held substantially constant.

[0012] Preferably, in some embodiments, three or more luminescence intensity measurements (B_1, B_2, B_3,...) are performed after the first A luminescence intensity measurement, the three or more luminescence intensity measurements being performed with the terminal voltage varied between the second B_1 and following luminescence intensity measurements and the illumination intensity held substantially constant.

[0013] Preferably, in some embodiments, three or more luminescence intensity measurements (B_1, B_2, B_3, ...) are performed after the first A luminescence intensity measurement, the three or more luminescence intensity measurements being performed with the illumination intensity varied between the second B_1 and following luminescence intensity measurements and the terminal voltage held substantially constant. In some embodiments, the series resistance is estimated at a plurality of areas of the diode device, to determine the spatial variation of series resistance across the device. In some embodiments, the first luminescence intensity A is measured with the terminal voltage at open circuit.

[0014] In accordance with another aspect of the present invention, there is provided a method of determining whether the series resistance at an area of a diode device exceeds a predetermined value, the method comprising the steps of: measuring a first luminescence intensity of the area of the device utilising an initial illumination intensity and terminal voltage; measuring a second luminescence intensity of the area utilising an alternative illumination intensity or terminal voltage; and determining from the first and second luminescence intensity measurements if the series resistance of the area of the device exceeds a predetermined value. Preferably, if a luminescence intensity is generated with non-zero illumination intensity, that luminescence intensity is corrected for the diffusion limited minority carrier lifetime of the material comprising the device by determining a reverse biased or zero bias condition of minimum luminescence intensity of the area.

[0015] The methods of the invention are highly suitable for use with photovoltaic devices.

[0016] In accordance with another aspect of the invention, there is provided a system for estimating the series resistance across a first area of a diode device, the system including: a luminescence detector for measuring a first luminescence intensity A from a first area of the device, utilising an initial illumination intensity and terminal voltage, a second luminescence intensity B_1 of the first area of the device utilising a varied illumination intensity or varied terminal voltage, and a third luminescence intensity B_2 of the first area of the device utilising a further varied illumination intensity or further varied terminal voltage; and a processor interconnected to the luminescence detector for interpolating or extrapolating luminescence intensity values from the second B_1 and third B_2 luminescence intensities so as to determine the illumination intensity and terminal voltage values that would reproduce the same luminescence signal as in the first luminescence intensity measurement A, and for calculating a series resistance $R_{S,}$ of the first area of the device from the determined illumination intensity and terminal voltage values.

[0017] Preferably, the processor is further adapted to correct at least one of the first, second and third luminescence intensities for the diffusion limited minority carrier lifetime of the material comprising the device.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings.

[0019] Fig. 1 shows a schematic view of a photoluminescence imaging setup suitable for use with preferred embodiments.

[0020] Fig. 2 shows schematically the sensor array of a camera and its segmentation into small sensor pixels. Each camera pixel has a sequential number represented by the index i, and images a corresponding area of a solar cell. The cell is therefore segmented into small areas with sizes corresponding to the size each camera pixel is able to map, which depends on the resolution of the camera sensor array and the imaging optics. The same index i represents therefore a corresponding area of the solar cell, so that Fig. 2 illustrates the segmentation of both the camera sensor array and the solar cell.

[0021] Fig. 3 illustrates two current-voltage curves of a solar cell part i at an illumination intensity that is equivalent to a short circuit current density of 7mA/cm^2. The broken curve 31 represents the current density plotted as a function of the terminal voltage $V_{terminal}$ and includes the effect of the series resistance R_S (assumed to be 10 Ωcm^2). The solid curve 32 represents the current density as a function of the voltage directly at the diode V_i, which is unaffected by the series resistance. The arrows in Fig. 3 show how a specific terminal voltage $V_{terminal,A}$ (tip of vertical arrow 34) and the local diode voltage $V_{i,A}$ (tip of horizontal arrow 35) relate to each other. The dashed vertical line 36 represents a constant value of diode voltage V_i.

[0022] Fig. 4 illustrates plots of the current density versus diode voltage for two different illumination intensities 41, 42. The distance between the curves is constant and equivalent to the difference in short circuit currents.

[0023] Fig. 5 and Fig. 6 illustrate plots of current density as a function of terminal voltage (broken lines) and as a function of diode voltage (solid lines) for two different illumination intensities 20mW/cm^2 (A) and 100mW/cm^2 (B), that are equivalent to short circuit current densities of 7mA/cm^2 and 36 mA/cm^2 respectively. Fig. 5 includes two vertical dotted arrows pointing to two terminal voltages that correspond to the same diode voltage, and demonstrates that for each terminal voltage $V_{terminal,A}$ there exists exactly one specific terminal voltage $V_{terminal,B}$ that corresponds to the same diode voltage. In Fig. 6 the vertical dotted arrows 61, 62 point to two operating points $B1$ and $B2$ where the terminal voltages $V_{terminal,B1}$ and $V_{terminal,B2}$ correspond to diode voltages $V_{i,B1}$ 65 and $V_{i,B2}$ 64 that are larger and smaller, respectively, than the diode voltage $V_{i,A}$ 66.

[0024] Fig. 7 illustrates the special case where the terminal voltage is changed within series B and the illumination intensity is changed between image A and series B but held constant between the images measured in series B. Measurement data from the images for pixel i are shown as dots. The measurement data of series B are interpolated and extrapolated as shown by a solid line 71. The luminescence intensity $I_{camera,A,i}$ (i.e. the intensity at pixel i of image A) can be found on the interpolated curve derived from images B (horizontal broken line). The difference in terminal voltages required to yield the same luminescence intensity in pixel i and to be used for the calculation of the local series resistance is indicated by $\Delta V_{terminal,BA}$. The measurement points are different from the ones displayed in Fig. 5 and Fig. 6.

[0025] Fig. 8 illustrates a graph similar to Fig. 7 but represents a more general scenario where the luminescence values in pixel i from series B are plotted as a function of $(\Delta V_{terminal,BA} / \Delta J_{light,AB})$, which is equivalent to the local series resistance. In this case both the terminal voltage and the illumination intensity may be varied between image A and images in series B and also within series B. Every value of $(\Delta V_{terminal,BA} / \Delta J_{light,AB})$ represents a possible local series resistance value, with the framed series resistance corresponding to the correct value.

[0026] Fig. 9 presents a flow chart of the calculation procedure of the method of the preferred embodiment.

DETAILED DESCRIPTION

[0027] In the following description the expressions 'local junction voltage' and 'local diode voltage' are equivalent and represented by V_i, and the terms 'terminal voltage' and 'bias' are equivalent.

[0028] To measure the spatially resolved series resistance of diode devices such as photovoltaic devices and solar cells, an experimental setup for luminescence imaging is needed. One form of suitable setup for photoluminescence imaging, illustrated schematically in Fig. 1, is described in PCT Publication WO2007/128060 entitled 'Method and System for Testing Indirect Bandgap Semiconductor Devices using Luminescence Imaging', the contents of which are incorporated by cross reference.

[0029] Normally, the current density of a solar cell and all its subsections is given as:

$$J_i = J_{light} - J_{d,i}(V_i)$$

where J_{light} is the light generated current, equal in most cases to the short circuit current of the cell and linear in the external illumination intensity so that a well defined variation of illumination intensity leads to a well defined variation of J_{light}. Under conditions of uniform illumination, J_{light} is considered to be uniform across a sample cell. The diode dark current $J_{d,i}$ is a function of the diode voltage V_i; the exact function $J_{d,i}(V_i)$ is complicated and depends on a number of normally unknown parameters, all of which can vary across the cell area.

[0030] Local luminescence intensities across a cell are measured in luminescence images, and can be correlated with the local diode voltage. For luminescence generated by photo-excitation (i.e. photoluminescence), the local luminescence intensity $I_{camera,i}$ contains two contributions, one exponentially dependent on the local diode voltage V_i and the other dependent on the illumination intensity but independent of the diode voltage:

$$I_{camera,i} = C_i \cdot exp(V_i/kT) + C_{off\text{-}set,i} \qquad (1)$$

where kT is the so-called thermal voltage and C_i is a calibration constant. For luminescence generated electrically (i.e. electroluminescence) the offset $C_{off\text{-}set,i}$ is zero.

[0031] For existing spatially resolved series resistance measurement methods, equation (1) is used to access the local diode voltage V_i. It is important to note that the constant C_i can vary significantly across the cell area i.e. from pixel to pixel; furthermore, because minority carrier lifetime and diffusion length vary with operating conditions, it can even vary for individual pixels. These dependencies need to be known and accounted for to interpret a luminescence signal accurately.

[0032] The contribution $C_{off\text{-}set,i}$ is constant for a specific illumination condition and is caused by the so-called diffusion limitation of the minority carrier lifetime, which is a property of the material from which the cell is composed. As discussed in T. Trupke *et al* Appl. Phys. Lett. 90 (2007) 093506, the measured camera signal has to be corrected for the contribution $C_{off\text{-}set,i}$. In practice, $C_{off\text{-}set,i}$ is obtained from the camera signal with the cell at short circuit or reverse terminal voltage condition.

[0033] The offset value $C_{off\text{-}set,i}$ for a given illumination intensity is measured by keeping the illumination intensity constant and reducing the terminal voltage to a sufficiently low value. 'Sufficiently low' means that the local diode voltage has to be small enough to yield negligible contribution to the total luminescence emission, i.e. the exponential term on the right hand side of equation (1) has to be close to zero or at least much smaller than $C_{off\text{-}set,i}$. For this purpose it is normally sufficient to operate the cell at short circuit. However in cases of extremely high local series resistance, the short circuit condition cannot provide a sufficiently low local diode voltage, causing a non-negligible contribution from the diode to the overall luminescence signal. In such cases the following procedure may be applied:

[0034] For the selected external light intensity, the solar cell is initially operated at short circuit condition ($V_{terminal} = 0$ V), and a luminescence image is taken by the camera. A subsequent image is taken at a reverse terminal voltage (e.g. $V_{terminal} = -0.1$ V), and the luminescence intensity at each camera sensor pixel *i* compared between the two images. If the intensity $I_{camera,i}$ at a pixel is lower in the reverse biased condition, another image with a bigger reverse bias (e.g. -0.2V) is taken, and the procedure repeated until each $I_{camera,i}$ reaches its minimum or an acceptably low value. All individual minimum values for $I_{camera,i}$ are recorded. A typical criterion to decide whether negligible diode contributions have been reached would be e.g. if no pixel changed by more than 10% when the reverse terminal voltage increased (i.e. made more negative) by 0.1V.

[0035] A corrected luminescence image consists of a luminescence image measured at any given operating point minus a 'correction luminescence image', which is measured using the same illumination intensity and measurement parameters but with the cell operated at short circuit or in reverse bias (i.e. with negligible diode contributions). The corrected luminescence intensity for each pixel thus consists solely of the first term on the right hand side of equation (1), i.e. the pure diode contribution. As mentioned above, electroluminescence images do not need to be corrected in this manner. For the purposes of the following discussion, all luminescence images are 'corrected' as described above, if necessary. The terms 'luminescence image' or 'luminescence intensity' or 'camera signal' thus describe corresponding quantities that have been corrected if required for the diffusion limited minority carrier lifetime.

[0036] The fundamental idea of the preferred embodiments of this invention is to find two different operating conditions A and B (with different terminal voltage and different illumination intensity) of a sample solar cell that correspond to the same local luminescence signal, and to use this information to calculate the series resistance as a function of position across the cell.

[0037] A key aspect of the preferred embodiments is that because identical luminescence signal implies identical local diode voltage V_i and thus identical local diode dark current density $J_{d,i}$, the unknown, complicated and laterally variable local current – voltage characteristics are eliminated from the analysis; all that is required is the knowledge that the diode current under both operating conditions A and B is the same.

[0038] If the local luminescence intensity is the same under two different operating conditions A and B, then the local series resistance $R_{s,i}$ can be quantified via a theoretical analysis of the light generated current density $J_{light,A}$ and $J_{light,B}$ and the terminal voltages $V_{terminal,A}$ and $V_{terminal,B}$. One or more of those quantities may be obtained via interpolation or extrapolation of the experimental data, as described below.

[0039] For two different operating conditions of a solar cell the following equations hold:

$$V_{terminal,A} = V_{i,A} - J_{i,A} \cdot R_{S,i} = V_{i,A} - (J_{light,i,A} - J_{d,i,A}) \cdot R_{S,i}$$
$$V_{terminal,B} = V_{i,B} - J_{i,B} \cdot R_{S,i} = V_{i,B} - (J_{light,i,B} - J_{d,i,B}) \cdot R_{S,i}$$

which can be rewritten

$$V_{terminal,A} - V_{terminal,B} = V_{i,A} - V_{i,B} + \{(J_{light,i,B} - J_{d,i,B}) - (J_{light,i,A} - J_{d,i,A})\} \cdot R_{S,i}$$

[0040] Previous luminescence-based R_S imaging methods had the shortcoming that the difference in current densities could not be determined precisely due to the unknown and spatially varying diode characteristics. Also, the dependency of the calibration constant C_i on the operation conditions of the cell was ignored, leading to an additional error.

[0041] For a given pixel i, the method proceeds as follows. If the two operating conditions A and B produce the same luminescence intensity, i.e. $I_{camera,i,A} = I_{camera,i,B}$, then $V_{i,A}=V_{i,B}$ from equation (1) (remembering that $C_{off\text{-}set,i}$ is negligible or zero in a corrected photoluminescence image), and therefore $J_{d,i,A}=J_{d,i,B}$. These two relations allow the above equation to be simplified and rearranged to yield:

$$R_{S,i}=\frac{V_{terminal,B}-V_{terminal,A}}{\left(J_{light,i,A}-J_{light,i,B}\right)}=\frac{\Delta V_{terminal,BA}}{\Delta J_{light,AB}} \qquad (2)$$

[0042] The advantage of this simplified formula (eqn (2)) for the local series resistance $R_{s,i}$ is that all quantities are directly accessible via the cell terminals or can obtained via interpolation or extrapolation of data that are accessible via the cell terminals. The difference in light generated current density $\Delta J_{light,AB}$ is easily obtained by measuring the short circuit current densities at light intensities A and B respectively.

[0043] Significantly, the method avoids any conversion of luminescence signal $I_{camera,i}$ into actual diode voltage V_i. Knowledge about the calibration constant C_i, its lateral variation and its variation with the cell operating conditions is not required.

[0044] In practice, one luminescence image is taken at operating condition A, which is a combination of illumination intensity $I_{illumination,A}$ and terminal voltage $V_{terminal,A}$. Preferably, image A is taken with no current being extracted from the cell, i.e. open circuit conditions, so that $V_{terminal,A} = V_{oc}$. A second luminescence image B is taken at a different illumination intensity $I_{illumination,B}$ and/or a different terminal voltage $V_{terminal,B}$.

[0045] As shown in Fig. 5 and Fig. 6, there are three possible scenarios for each pixel: its luminescence intensity in image B can either be larger, identical or smaller compared to image A. If the intensity in the two images is the same, equation (2) can be used to calculate the series resistance at that pixel.

[0046] If on the other hand the luminescence intensity is higher in image B, the local diode voltage must also be higher (from equation (1)). As seen in Fig. 6 a higher diode voltage in series B corresponds to a higher terminal voltage and thus to a smaller difference in terminal voltages $\Delta V_{terminal,BA}$, and according to equation (2) this corresponds to a $R_{S,i}$ value that is below the current value. Thus from a single luminescence intensity comparison $I_{camera,B} > I_{camera,A}$ only a lower limit for the series resistance can be determined. Using the same arguments as above an upper limit for the series resistance can be determined from a single luminescence intensity comparison $I_{camera,B} < I_{camera,A}$.

[0047] An interpolation method can be used to obtain actual values for $R_{S,i}$, rather than just upper or lower limits. The interpolation needs at least two images taken in series B, with either $I_{illumination,B}$ or $V_{terminal,B}$ (or both) changed as a parameter. As an example we will describe a method where the illumination intensity is held constant for all images within a series B and the terminal voltage is varied. However a method where the terminal voltage is held constant and the illumination intensity varied works in an analogous way.

[0048] For each pixel the dependency of the local luminescence signal as a function of the varied parameter (i.e. the terminal voltage in the example discussed here) can be plotted, and the resulting curve interpolated or extrapolated to provide the parameter value (e.g. voltage) that corresponds to the same luminescence intensity as obtained in image A.

[0049] Fig. 7 shows an example where four series B measurements have been performed and the measured luminescence intensities plotted as a function of the terminal voltage $V_{terminal}$. A fitting curve 71 is calculated between those four points, and the terminal voltage in series B that corresponds to the same luminescence intensity as in A obtained as the intersection 72 by interpolation or extrapolation. This interpolation/extrapolation procedure avoids the necessity to find experimentally suitable operating conditions for each pixel to match the camera signals in A and B.

[0050] The correct parameter (terminal voltage in our example) can thus be obtained for each pixel from the measured data points by interpolation or extrapolation. The quantitative local value for R_S can then be calculated for each pixel according to equation (2) using that interpolated or extrapolated parameter.

[0051] Preferably, at least one image in series B is acquired with terminal voltage higher than that used for image A, to avoid having to extrapolate the series B curve. In a typical procedure for a silicon-based solar cell, image A would be acquired with illumination intensity $I_{illumination,A} = 20$ mW/cm^2 and terminal voltage $V_{terminal,A} = V_{oc}$, and series B would contain five images acquired with illumination intensity $I_{illumination,B} = 100$ mW/cm^2 (approximately 1 Sun) and terminal voltages $V_{terminal,B}$ beginning slightly above V_{oc} and stepping down by 20, 50, 100 and 200 mV respectively.

[0052] In a more general variation of this method both parameters (terminal voltage and the illumination intensity) can be varied in the series B. Fig. 8 shows a graph 80 of I_{camera} vs $\frac{V_{terminal,B} - V_{terminal,A}}{J_{light,A} - J_{light,B}}$ to which interpolation/extrapolation is applied as described above to yield the local series resistance value.

[0053] These analysis procedures can be repeated in an automated fashion, i.e. using appropriate computer algorithms, for each subsection i of the solar cell, i.e. for each pixel. The time required to measure local series resistance across an entire solar cell is of order 1 second to 10 minutes, and typically 30 seconds to 2 minutes, depending on several factors including the size and quality of the cell, the desired pixelation, the signal-to-noise ratio, and the required measurement accuracy. It should be noted that it is often unnecessary to determine accurate *absolute* values of the local series resistance, as *relative* local series resistance values can also be useful for identifying defective regions of a sample cell for example. A significant benefit of the methods of the present invention is that they enable local series resistance values, absolute or relative, to be estimated with the influence of varying local diode properties removed or strongly reduced.

[0054] In general the relationship between the luminescence intensity and the varied parameter in series B is non-linear, so that the method will be more accurate the more images are measured in the series B. The results will also be more accurate if the chosen experimental parameters in series B are closer to the actual values that provide $I_{camera,B} = I_{camera,A}$.

[0055] The measurement range of $R_{S,i}$ values can be changed with the difference in light intensities $\Delta J_{light,AB}$. This alters the fraction $\frac{\Delta V_{terminal,BA}}{\Delta J_{light,AB}}$ and therefore the difference in terminal voltage $\Delta V_{terminal,BA}$ that is needed to measure a particular series resistance $R_{S,i}$.

[0056] For more rapid measurements, say for mass production purposes, a threshold series resistance $R_{s,threshold}$ can be defined, where the number of pixels with $R_S > R_{S,threshold}$ could be used as a rating / sorting criterion. After the first luminescence image A is measured with terminal voltage $V_{terminal,A}$, a second image can be measured with well defined terminal voltage $V_{terminal,B} = R_{s,threshold} \cdot \Delta J_{light,AB} - V_{terminal,A}$. This allows determination of all pixels for which the local series resistance is above or below that threshold value $R_{s,threshold}$.

[0057] It should be noted that:

1. The chosen light intensities and terminal voltages discussed here are non-limiting examples. For example the procedure is also valid with higher light intensity for image A and a lower light intensity for images in series B, as well as for a mix of lower and higher light intensities for images in series B.

2. The sensitivity regarding the measurement of the local series resistance can be varied by altering the difference of biasing illumination intensity and therefore the difference in light generated current.

3. In some cases it might be of advantage to measure the series B images at a constant terminal voltage but with varying biasing light intensity.

[0058] The measurement method involves the following main steps, with a flow chart 90 as set out in Fig. 9:

I. A first luminescence image is measured with cell operating conditions A, i.e. with given illumination intensity $I_{illumination,A}$ and terminal voltage $V_{terminal,A}$. Measuring a luminescence image consists of the sub-steps:

  i. Measuring a first image with given illumination intensity at a specific terminal voltage.

  ii. Measuring a second image with the same illumination intensity but with the cell operated at a terminal voltage at which the diode does not contribute to the luminescence emission. This is either at short circuit condition or in reverse terminal voltage.

  iii. Subtracting the second image from the first image.

  iv. Steps ii. and iii. are not required for luminescence images measured with zero illumination intensity, e.g. electroluminescence images.

II. A second luminescence image is measured with cell operating conditions B_1, where $I_{illumination,B1} \neq I_{illumination,A}$ and/or $V_{terminal,B1} \neq V_{terminal,A}$.

III. A third luminescence image is measured with cell operating conditions B_2, where the illumination intensity and/or the terminal voltage are varied compared to B_1.

IV. For each pixel, the luminescence intensities from II) and III) are plotted as a function of the parameter(s) changed with respect to operating condition A, i.e. $\frac{\Delta V_{terminal,BA}}{\Delta J_{light,AB}}$.

V. For each pixel the value of luminescence intensity of image A has to be found in series B; this value is found on an interpolated or extrapolated curve of data points B where the camera signal $I_{camera,B}$ is plotted as a function of $\frac{\Delta V_{terminal,BA}}{\Delta J_{light,AB}}$. The corresponding value for $\frac{\Delta V_{terminal,BA}}{\Delta J_{light,AB}}$ is equivalent to $R_{S,i}$.

VI. The series resistance R_S is calculated for each pixel according to steps I to V.

[0059] Variations of this method include

I. A method where only two luminescence images A and B are measured and where either an upper or lower limit for the series resistance is obtained for each pixel.

II. A method in which three or more luminescence images (B_1, B_2, B_3, B_4, …) are measured after the first image A. All images B are measured where at least one parameter (illumination intensity or terminal voltage) is altered. The abovementioned interpolation or extrapolation is then performed with more data points and is thus more accurate.

III. A method where the previously described correction process (i.e. subtraction of photoluminescence images measured at short circuit or in reverse bias) is omitted; this results in shorter measurement time but also in less accurate data.

IV. A method in which at least one image is measured with zero illumination intensity (i.e. electroluminescence imaging). In that case the offset due to the diffusion limited lifetime is zero and the correction is unnecessary.

V. A method in which the series of images B consists of electroluminescence images, i.e. luminescence images with zero illumination intensity and variable terminal voltage $V_{terminal,B}$.

[0060] The method can be readily implemented on the imaging hardware of the experimental system illustrated in Fig. 1. In this arrangement, the imaging computer 550 captures images on demand of solar cells 540 under the control of illumination source 510. These images are then processed by the imaging computer in accordance with the aforementioned method so as to provide an output estimate of spatial variations of the series resistance across the device under examination.

[0061] The arrangement of Fig. 1 can obviously be extended to many different environments. For example, assembly line environments, batch processing environments, and test environments are all possible environments in which the method of the preferred embodiment can be utilised.

[0062] The forgoing describes preferred forms of the present invention only. Although the invention has been described with reference to specific examples it will be appreciated by those skilled in the art that the invention may be embodied in many other forms. Modifications obvious to those skilled in the art can be made thereto without departing from the scope of the invention.

We claim:

1. A method of estimating the series resistance at an area of a diode device, said method comprising the steps of:

(a) measuring a first luminescence intensity A of said area of said device utilising an initial illumination intensity and terminal voltage;

(b) measuring a second luminescence intensity B_1 of said area utilising a varied illumination intensity or varied terminal voltage;

(c) measuring a third luminescence intensity B_2 of said area in which at least one parameter is varied compared to said measuring of said second corrected luminescence intensity B_1, said parameters being the terminal voltage and the illumination intensity;

(d) interpolating or extrapolating the luminescence intensity values from said second B_1 and third B_2 luminescence intensities to determine the values of said parameters that would produce said first luminescence intensity A; and

(e) using the determined parameter values to estimate the series resistance at said area.

2. A method as claimed in claim 1 wherein said area corresponds to one or more pixels of a luminescence image.

3. A method as claimed in claim 1 or claim 2 wherein at least one luminescence intensity is generated with zero illumination intensity.

4. A method as claimed in any one of the previous claims wherein, if a luminescence intensity is generated with non-zero illumination intensity, that luminescence intensity is corrected for the diffusion limited minority carrier lifetime of the material comprising said device by determining a reverse biased or zero bias condition of minimum luminescence intensity of said area.

5. A method as claimed in any one of the previous claims wherein the illumination intensity is varied between the first luminescence intensity measurement A and the second luminescence intensity measurement B_1, and the terminal voltage is held substantially constant.

6. A method as claimed in any one of claims 1-4 wherein the terminal voltage is varied between the first luminescence intensity measurement A and the second luminescence intensity measurement B_1, and the illumination intensity is held substantially constant.

7. A method as claimed in any one of the previous claims wherein the terminal voltage is varied between the second B_1 and third B_2 luminescence intensity measurements and the illumination intensity is held substantially constant.

8. A method as claimed in any one of claims 1-6 wherein the illumination intensity is varied between the second B_1 and third B_2 luminescence intensity measurements and the terminal voltage is held substantially constant.

9. A method as claimed in any one of the previous claims wherein three or more luminescence intensity measurements (B_1, B_2, B_3,...) are performed after the first A luminescence intensity measurement, said three or more luminescence intensity measurements being performed with the terminal voltage varied between the second B_1 and following luminescence intensity measurements and the illumination intensity held substantially constant.

10. A method as claimed in any one of claims 1-8 wherein three or more luminescence intensity measurements (B_1, B_2, B_3, ...) are performed after the first A luminescence intensity measurement, said three or more luminescence intensity measurements being performed with the illumination intensity varied between the second B_1 and following luminescence intensity measurements and the terminal voltage held substantially constant.

11. A method as claimed in any of the previous claims wherein said series resistance is estimated at a plurality of areas of said diode device, to determine the spatial variation of series resistance across said device.

12. A method as claimed in any one of the previous claims, wherein the first luminescence intensity A is measured with the terminal voltage at open circuit.

13. A method of determining whether the series resistance at an area of a diode device exceeds a predetermined value, said method comprising the steps of:

(a) measuring a first luminescence intensity of said area of said device utilising an initial illumination intensity and terminal voltage;

(b) measuring a second luminescence intensity of said area utilising an alternative illumination intensity or terminal voltage; and

(c) determining from the first and second luminescence intensity measurements if the series resistance of said area of said device exceeds a predetermined value.

14. A method as claimed in claim 13 wherein said area corresponds to one or more pixels of a luminescence image.

15. A method as claimed in claim 13 or claim 14 wherein at least one luminescence intensity is generated with zero illumination intensity.

16. A method as claimed in any one of claims 13-15 wherein, if a luminescence intensity is generated with non-zero illumination intensity, that luminescence intensity is corrected for the diffusion limited minority carrier lifetime of the material comprising said device by determining a reverse biased or zero bias condition of minimum luminescence intensity of said area.

17. A method as claimed in any one of claims 13 to 16, wherein the first luminescence intensity A is measured with the terminal voltage at open circuit.

18. A method as claimed in any one of the previous claims wherein the device is a photovoltaic device.

19. A system for estimating the series resistance across a first area of a diode device, the system including:

a luminescence detector for measuring a first luminescence intensity A from a first area of the device, utilising an initial illumination intensity and terminal voltage, a second luminescence intensity B_1 of said first area of the device utilising a varied illumination intensity or varied terminal voltage; and a third luminescence intensity B_2 of said first area of the device utilising a further varied illumination intensity or further varied terminal voltage; and a processor interconnected to the luminescence detector for interpolating or extrapolating luminescence intensity values from said second B_1 and third B_2 luminescence intensities so as to determine the illumination intensity and terminal voltage values that would reproduce the same luminescence signal as in said first luminescence intensity measurement A, and for calculating a series resistance R_S, of said first area of the device from the determined illumination intensity and terminal voltage values .

20. A system as claimed in claim 19, wherein said processor is further adapted to correct at least one of said first, second and third luminescence intensities for the diffusion limited minority carrier lifetime of the material comprising said device.

21. A method of estimating the likely series resistance across a first area of a photovoltaic diode device, substantially as herein described with reference to any one of the embodiments of the invention illustrated in the accompanying drawings and/or examples.

22. A system for estimating the series resistance across an area of a diode device, said system implementing the method of any one of claims 1 to 18.

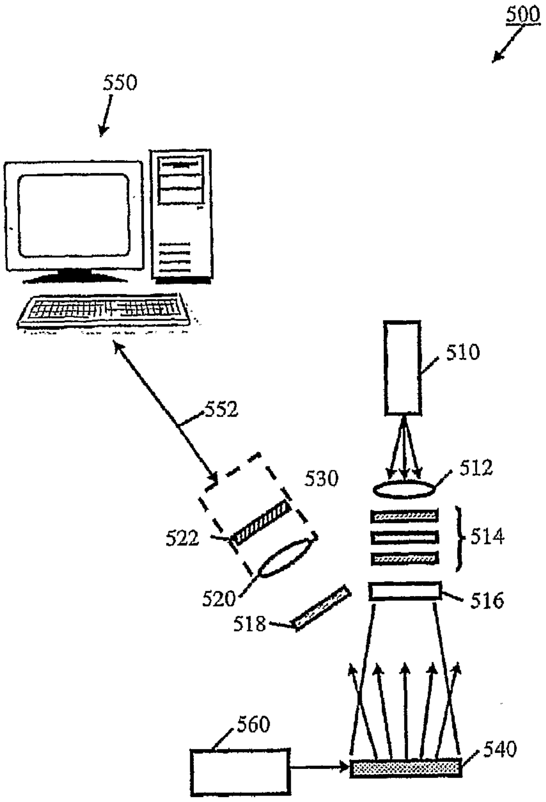

Fig. 1

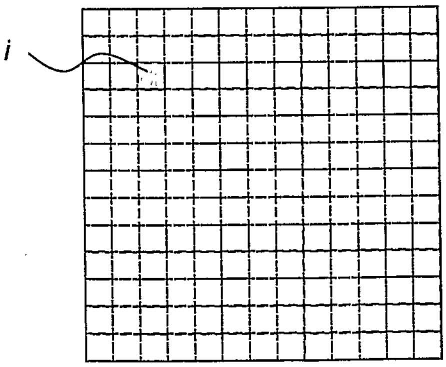

Fig. 2

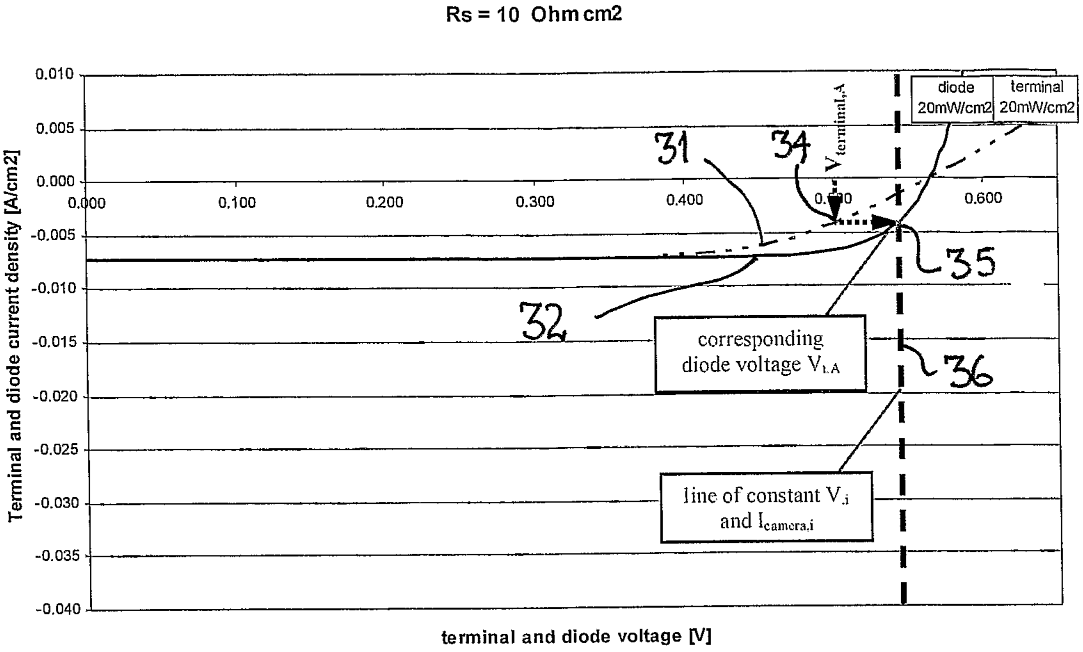
Rs = 10 Ohm cm2
Terminal and diode current density [A/cm2]
terminal and diode voltage [V]
0.010
0.005
0.000
-0.005
-0.010
-0.015
-0.020
-0.025
-0.030
-0.035
-0.040
0.000
0.100
0.200
0.300
0.400
0.500
0.600
diode 20mW/cm2
terminal 20mW/cm2
$V_{terminal,A}$
31
34
35
32
36
corresponding diode voltage $V_{i,A}$
line of constant $V_{,i}$ and $I_{camera,i}$

Fig. 3

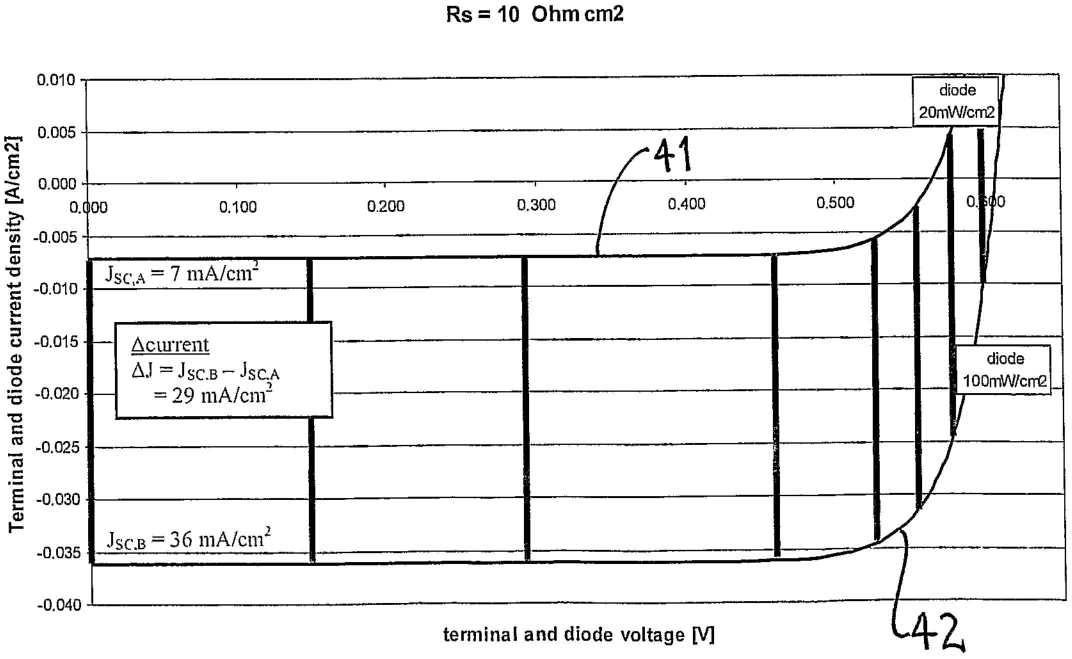
Rs = 10 Ohm cm2
Terminal and diode current density [A/cm2]
terminal and diode voltage [V]
0.010
0.005
0.000
-0.005
-0.010
-0.015
-0.020
-0.025
-0.030
-0.035
-0.040
0.000
0.100
0.200
0.300
0.400
0.500
0.600
diode 20mW/cm2
diode 100mW/cm2
41
42
$J_{SC,A} = 7$ mA/cm^2
Δcurrent
$\Delta J = J_{SC,B} - J_{SC,A}$
$= 29$ mA/cm^2
$J_{SC,B} = 36$ mA/cm^2

Fig. 4

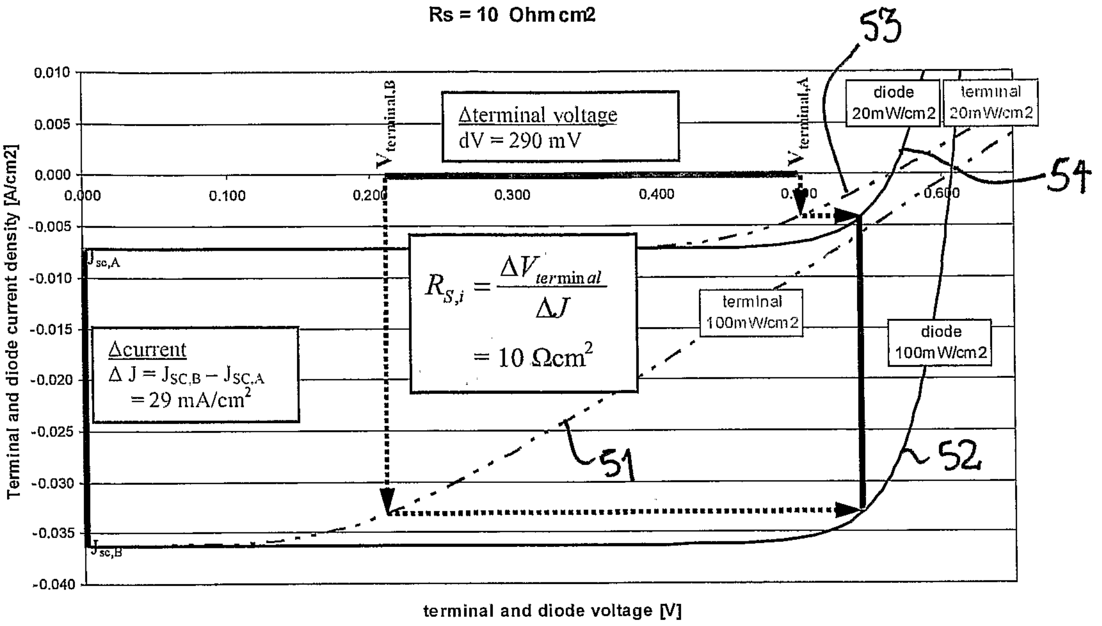
Rs = 10 Ohm cm2
53
54
51
52
0.010
0.005
0.000
-0.005
-0.010
-0.015
-0.020
-0.025
-0.030
-0.035
-0.040
0.000
0.100
0.200
0.300
0.400
0.500
0.600
Terminal and diode current density [A/cm2]
terminal and diode voltage [V]
V terminal,B
V terminal,A
Δterminal voltage
dV = 290 mV
diode 20mW/cm2
terminal 20mW/cm2
terminal 100mW/cm2
diode 100mW/cm2
J sc,A
J sc,B
Δcurrent
Δ J = J SC,B − J SC,A
= 29 mA/cm2
$R_{S,i} = \frac{\Delta V_{terminal}}{\Delta J}$
= 10 Ωcm2

Fig. 5

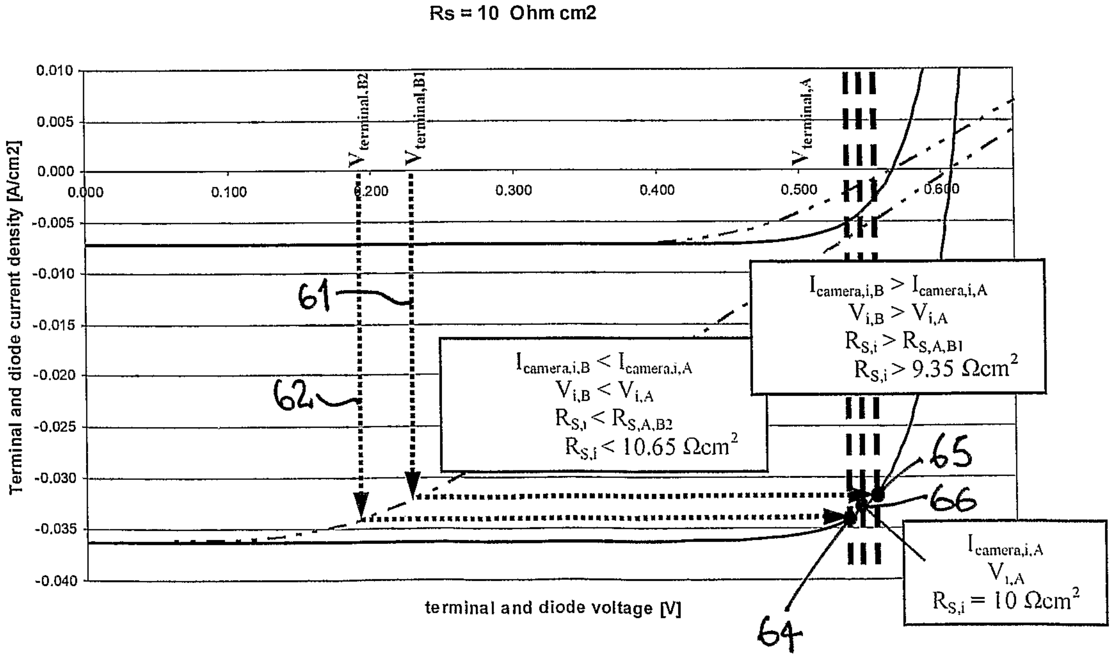
Rs = 10 Ohm cm2
0.010
0.005
0.000
-0.005
-0.010
-0.015
-0.020
-0.025
-0.030
-0.035
-0.040
0.000
0.100
0.200
0.300
0.400
0.500
0.600
Terminal and diode current density [A/cm2]
terminal and diode voltage [V]
V terminal,B2
V terminal,B1
V terminal,A
61
62
64
65
66
I camera,i,B > I camera,i,A
V i,B > V i,A
R S,i > R S,A,B1
R S,i > 9.35 Ωcm2
I camera,i,B < I camera,i,A
V i,B < V i,A
R S,i < R S,A,B2
R S,i < 10.65 Ωcm2
I camera,i,A
V i,A
R S,i = 10 Ωcm2

Fig. 6

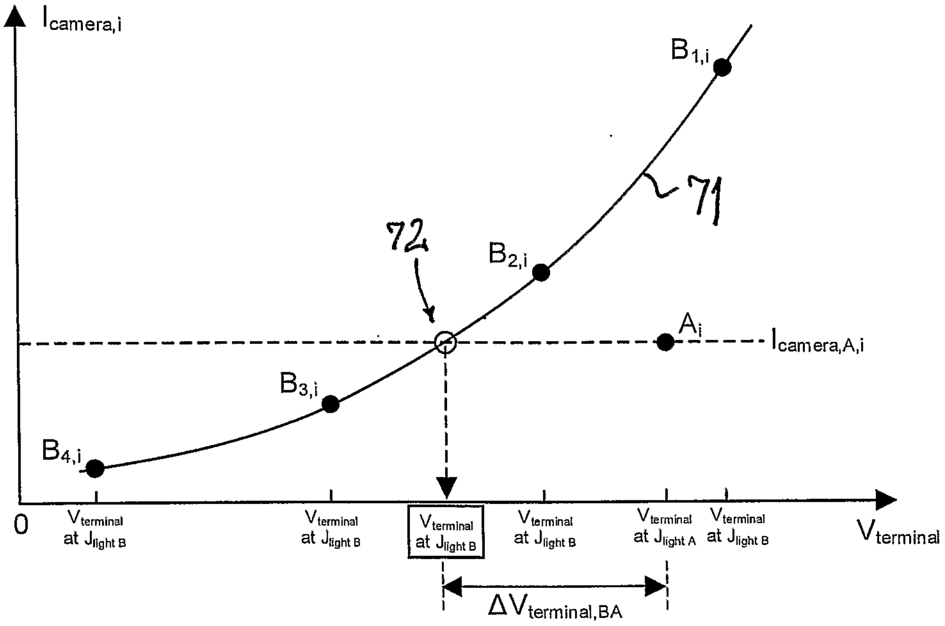
$I_{camera,i}$
$B_{1,i}$
71
72
$B_{2,i}$
A_i
$I_{camera,A,i}$
$B_{3,i}$
$B_{4,i}$
0
$V_{terminal}$ at $J_{light\ B}$
$V_{terminal}$ at $J_{light\ B}$
$V_{terminal}$ at $J_{light\ B}$
$V_{terminal}$ at $J_{light\ B}$
$V_{terminal}$ at $J_{light\ A}$
$V_{terminal}$ at $J_{light\ B}$
$V_{terminal}$
$\Delta V_{terminal,BA}$

Fig. 7

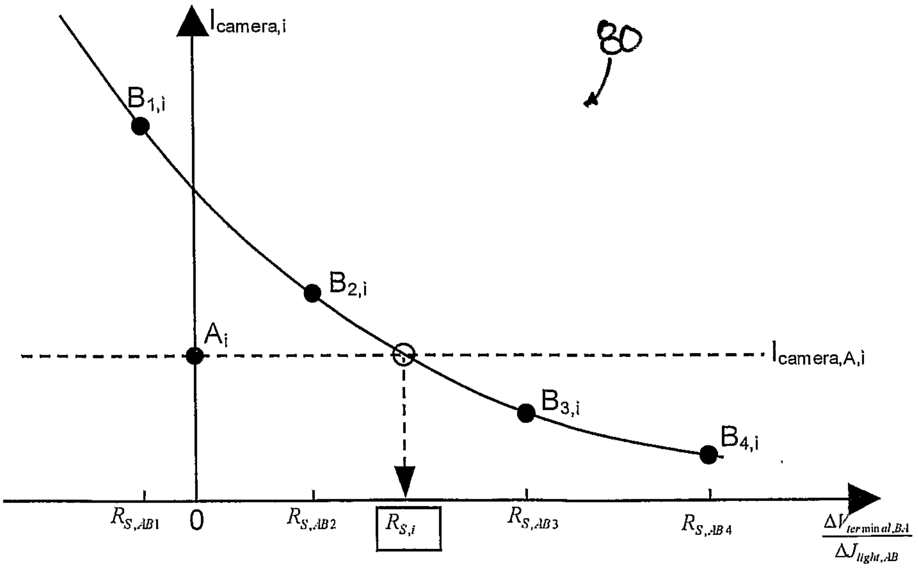
$I_{camera,i}$
80
$B_{1,i}$
$B_{2,i}$
A_i
$I_{camera,A,i}$
$B_{3,i}$
$B_{4,i}$
$R_{S,AB1}$
0
$R_{S,AB2}$
$R_{S,i}$
$R_{S,AB3}$
$R_{S,AB4}$
$\frac{\Delta V_{terminal,BA}}{\Delta J_{light,AB}}$

Fig. 8

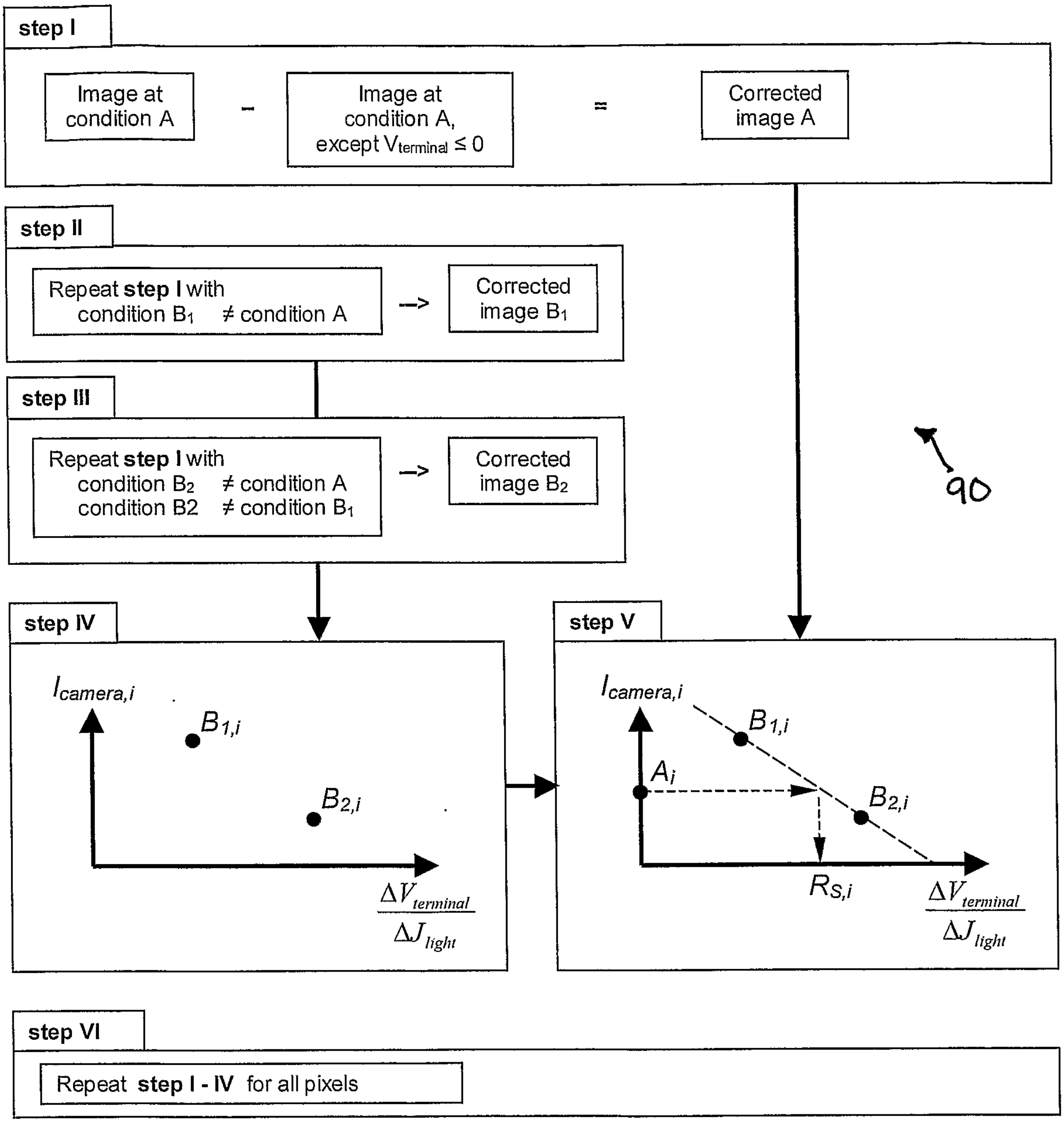
step I
Image at condition A
-
Image at condition A, except $V_{terminal} \leq 0$
=
Corrected image A
step II
Repeat **step I** with condition B_1 ≠ condition A
-->
Corrected image B_1
step III
Repeat **step I** with condition B_2 ≠ condition A condition B2 ≠ condition B_1
-->
Corrected image B_2
90
step IV
$I_{camera,i}$
$B_{1,i}$
$B_{2,i}$
$\frac{\Delta V_{terminal}}{\Delta J_{light}}$
step V
$I_{camera,i}$
$B_{1,i}$
A_i
$B_{2,i}$
$R_{S,i}$
$\frac{\Delta V_{terminal}}{\Delta J_{light}}$
step VI
Repeat **step I - IV** for all pixels

Fig. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2009/000506

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl. *H01L 21/66* (2006.01) *G01R 31/26* (2006.01)

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)

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)
INSPEC, WPI and EPODOC (keywords): solar cell, solar panel, photovoltaic, resistance, luminescence, photoluminescence, voltage, region, area, predict, interpolate, extrapolate, image, camera, pixel, illuminate, irradiate and similar terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2007/128060 A1 (NEW SOUTH WALES INNOVATIONS PTY LTD) 15 November 2007 See abstract, page 1 line 13, page 15 lines 6-18, figures 2a-2c, figure 5 items 530 and 550	13,14,18,19,22
X	HINKEN, D et al., 'Series resistance imaging of solar cells by voltage dependent electroluminescence', Applied Physics Letters, 2007, vol 91, page 182104 See abstract, paragraph 6 and 7, equations 1-9	13-15,18,19,22
X	RAMSPECK, K et al., 'Recombination current and series resistance imaging of solar cells by combined luminescence and lock in thermography', Applied Physics Letters, 2007, vol 90, page 153502 See abstract, paragraph 4, equations 1-4	13-15,18,19,22
X	TRUPKE, T et al., 'Spatially resolved series resistance of silicon solar cells obtained from luminescence imaging', Applied Physics Letters, 2007, vol 90, page 093506 See abstract, paragraphs 2-10, figure 1	13,14,16-20,22
X	US 2007/0048884 A1 (NAGEL) 1 March 2007 See abstract, figure 7 item 24	19

☒ Further documents are listed in the continuation of Box C ☒ See patent family annex

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 20 May 2009	Date of mailing of the international search report 27 MAY 2009
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. +61 2 6283 7999	Authorized officer **Nathan Madsen** AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No : +61 2 6222 3612

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2009/000506

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: **21**
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

Claim 21 is an omnibus claim which fails to meet the requirements of Rule 6.2(a) and thus no search or opinion will be established regarding this claim.

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

[See supplemental box]

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☒ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Supplemental Box
(To be used when the space in any of Boxes I to IV is not sufficient)

Continuation of Box No III (Lack of Unity of Invention):

This International Application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept. In assessing whether there is more than one invention claimed, I have given consideration to those features which can be considered to potentially distinguish the claimed combination of features from the prior art. Where different claims have different distinguishing features they define different inventions. This International Searching Authority has found that there are different inventions as follows:

- Claims 1-12 are directed to a method of estimating the series resistance at an area of a diode device comprising the steps of: measuring a first luminescence intensity utilising an initial illumination intensity and terminal voltage; measuring a second luminescence intensity utilising varied illumination intensity or voltage; and measuring a third luminescence intensity utilising further varied illumination intensity and/or voltage. It is considered that measuring a third luminescence intensity comprises a first distinguishing feature.

- Claims 13-18, and 22 are directed to a method of determining whether the series resistance at an area of a diode device exceeds a predetermined value comprising the steps of: measuring a first luminescence intensity of an area of said device utilising an initial illumination intensity and terminal voltage; measuring a second luminescence intensity of an area of said device utilising varied illumination intensity or terminal voltage; and, determining from first and second luminescence intensity measurements whether the series resistance at an area of a diode device exceeds a predetermined value. It is considered that determining whether the series resistance at an area of a diode device exceeds a predetermined value comprises a second distinguishing feature.

- Claims 19 and 20 are directed to a system for estimating the series resistance across a first area of a diode device comprising a luminescence detector and a processor interconnected to the luminescence detector. It is considered that a processor interconnected to the luminescence detector comprises a third distinguishing feature.

PCT Rule 13.2, first sentence, states that unity of invention is only fulfilled when there is a technical relationship among the claimed inventions involving one or more of the same or corresponding special technical features. PCT Rule 13.2, second sentence, defines a special technical feature as a feature which makes a contribution over the prior art. The only feature common to all of the claims is measuring the luminescence, wherein the only feature common to the claims defined by the first two inventions (claims 1-12 and 13-18, 22) is measuring first and second luminescence intensities at particular illumination intensities and terminal voltages. However this common feature is generic in the art. This means that the common feature can not constitute a special technical feature within the meaning of PCT Rule 13.2, second sentence, since it makes no contribution over the prior art. Because the common feature does not satisfy the requirement for being a special technical feature it follows that it cannot provide the necessary technical relationship between the identified inventions. Therefore the claims do not satisfy the requirement of unity of invention *a posteriori*.

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	KASEMANN, M et al., 'Comparison of luminescence imaging and illuminated lock-in thermography on silicon solar cells', Applied Physics Letters, 2006, vol 89, page 224102 See all of document	1-20, 22
A	US 2005/0252545 A1 (NOWLAN et al.) 17 November 2005 See all of document	1-20, 22
A	KOSHKA, Y et al., 'Scanning room-temperature photoluminescence in polycrystalline silicon', Applied Physics Letters, 1999, vol 74, page 1555 See all of document	1-20, 22
A	DE 19738302 A1 (ZAE BAYERN [DE]) 4 March 1999 English abstract retrieved from EPODOC database See all of document	1-20, 22
A	CN 86101321 A (XI-AN JIAOTONG UNIV.) 21 October 1987 English abstract retrieved from EPODOC database See all of document	1-20, 22

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
WO	2007128060	EP	2024716				
US	2007048884	DE	102005040010	EP	1758178	JP	2007059907
US	2005252545	NONE					
DE	19738302	NONE					
CN	86101321	NONE					

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX