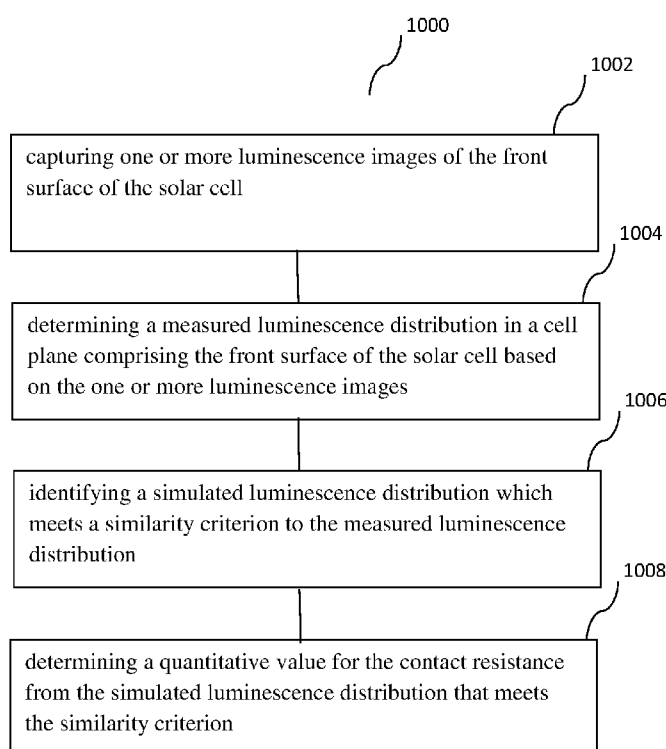




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- (54) Title: A METHOD AND SYSTEM FOR DETERMINING THE CONTACT RESISTANCE OF A SOLAR CELL



(57) Abstract: A method and system for determining the contact resistance of a solar cell having a front electrode grid on a front surface thereof. The method comprises the steps of capturing one or more luminescence images of the front surface of the solar cell; determining a measured luminescence distribution in a cell plane comprising the front surface of the solar cell based on the one or more luminescence images; identifying a simulated luminescence distribution which meets a similarity criterion to the measured luminescence distribution; and determining a quantitative value for the contact resistance from the simulated luminescence distribution that meets the similarity criterion.

Figure 10



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A METHOD AND SYSTEM FOR DETERMINING THE CONTACT RESISTANCE OF A SOLAR CELL

FIELD OF INVENTION

- 5 The present invention relates broadly a method and system for determining the contact resistance of a solar cell, and in particular to a method and system for determining the contact resistance of a solar cell having a front electrode grid on a front surface thereof.

BACKGROUND

- 10 The present invention is related broadly to the field of photoluminescence, electroluminescence, or generally luminescence imaging of semiconductor structures. Amongst the various contributors to series resistance in a solar cell, the contact resistance ρ_C between the metal electrode and the highly doped semiconductor layers figures prominently because it often makes a large impact to the device efficiency, and also because its magnitude
15 varies widely depending on the cell architecture (phosphorus emitter, boron emitter, heterojunction, passivated contacts), the metallization technology used to form the contact (screen printing, ink jet seed layer, direct plating), the carrier concentration in the highly doped semiconductor layer, the metallization material used (even among commercially available screen print silver pastes, there is a large spread in the ability to form high quality
20 contacts), and the processing conditions. As a result, it is not surprising to survey the market for conventional screen printed solar cells similar in appearance, and find that the front metal grid contact resistance can range anywhere from 1 to 20 $\text{m}\Omega\text{-cm}^2$. These values of contact resistance translates to roughly 0.03-0.6 Ωcm^2 series resistance R_s for the solar cell, a range which spans from insignificantly small to overwhelmingly large, when considering the fact
25 that good quality screen printed cells in the market have about 0.5 Ωcm^2 R_s in total. Therefore, contact resistance is a parameter that should be closely monitored in solar cell design, optimization, design-of-experiments (DOE) and process control efforts in the production line.

- Unfortunately, in reality contact resistance ρ_C is one of the least measured parameters because
30 existing measurement methods are tedious, and either destroys the cell of interest, or requires the fabrication of special test structures. One, to date considered the best established, of these is the transmission-line method (TLM) [1], which requires as sample preparation laser-cutting the cell into disconnected sections of parallel metal fingers. Another method is the Correscan method [5], which drags a fine needle across the solar cell surface which is destructive in the
35 measurement process. Moreover, both methods are slow, requiring many minutes if ρ_C is to be determined on multiple points on the solar cell, notwithstanding sample preparation time. Obviously any measurement method that involves extra sample preparation steps and

destroys the cell in question are not compatible with the production line environment, and can be performed only sparingly in failure analysis and research type settings.

Embodiments of the present invention provide a method and system for determining the contact resistance of a solar cell having a front electrode grid on a front surface thereof that seek to address at least one of the above problems.

SUMMARY

In accordance with a first aspect of the present invention, there is provided a method for determining the contact resistance of a solar cell having a front electrode grid on a front surface thereof, the method comprising the steps of capturing one or more luminescence images of the front surface of the solar cell; determining a measured luminescence distribution in a cell plane comprising the front surface of the solar cell based on the one or more luminescence images; identifying a simulated luminescence distribution which meets a similarity criterion to the measured luminescence distribution; and determining a quantitative value for the contact resistance from the simulated luminescence distribution that meets the similarity criterion.

In accordance with a second aspect of the present invention, there is provided a system for determining the contact resistance of a solar cell having a front electrode grid on a front surface thereof, the system comprising an imaging unit for capturing one or more luminescence images of the front surface of the solar cell; and a processing unit for determining a measured luminescence distribution in a cell plane comprising the front surface of the solar cell based on the one or more luminescence images, for identifying a simulated luminescence distribution which meets a similarity criterion to the measured luminescence distribution, and for determining a quantitative value for the contact resistance from the simulated luminescence distribution that meets the similarity criterion.

BRIEF DESCRIPTION OF THE DRAWINGS

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, in which:

Figure 1 shows a schematic drawing illustrating a network model of the solar cell, which depicts the solar cell plane as a multitude of diodes interconnected by resistors, for use in an example embodiment.

Figure 2 a) shows a schematic drawing illustrating a silicon wafer solar cell with an H-pattern front electrode grid.

Figure 2 b) shows a schematic drawing illustrating a Finite-element model (FEM) of the solar cell of Figure 2 a).

Figure 3 shows a flow chart of the methodology in an example embodiment.

Figure 4 shows a schematic drawing illustrating a luminescence imaging and electrical probing setup for the H-pattern front electrode grid solar cell according to the example embodiment of Figure 3.

5 Figure 5 shows images illustrating the regions of interest (ROI) used to describe the voltage variations along the cell plane, for a) the left busbar single-busbar biased image, b) the middle busbar single-busbar biased image, c) the right busbar single-busbar biased image, d) the open-circuit photoluminescence images.

Figure 6 shows a comparison of the experimental luminescence images according to an example embodiment to the simulated images, for an example three-busbar silicon wafer solar cell at three different biasing and illumination conditions.

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Figure 7 shows a flow chart of the methodology in another example embodiment.

Figure 8 shows a schematic drawing illustrating a luminescence imaging and electrical probing setup for the H-pattern front electrode grid solar cell according to the example embodiment of Figure 7.

15 Figure 9 shows images illustrating the regions of interest (ROI) used to describe the voltage variations along the cell plane, for a) left side line light source open circuit image, b) right side line light source open circuit image, c) the open-circuit photoluminescence image under uniform illumination.

Figure 10 shows a flowchart illustrating a method for determining the contact resistance of a solar cell having a front electrode grid on a front surface thereof, according to an example embodiment.

20

Figure 11 shows a schematic diagram illustrating a system for determining the contact resistance of a solar cell having a front electrode grid on a front surface thereof, according to an example embodiment.

25 DETAILED DESCRIPTION

Example embodiments of the invention described herein provide a method and system for determining the contact resistance between the metal electrode grid and the semiconductor layer of a solar cell, by inducing current to flow laterally along the metal fingers, either by applying an electrical bias to the solar cell at suitable points on the metal cathode and anodes, or by applying a highly non-uniform illumination pattern, and then measuring simultaneously the luminescence intensity distribution in the solar cell plane. The luminescence intensity distribution is either categorized by comparing features of the distribution to those of calibration samples, or analyzed using a network model of the solar cell, which depicts the solar cell plane as infinitesimal diodes interconnected by resistors.

30

35 In one embodiment, it has been recognized by the inventors that extracting the contact resistance information can be achieved by simulating the luminescence of the solar cell using

a network model, more particular using a finite-element or finite difference computer model with a fine mesh that divides the electrode metal grid lines into e.g. 2mm segments. A fitting procedure is performed wherein the simulated distributions are compared to the corresponding experimentally captured images, in an iterative manner that seeks to minimize the difference between the simulated and experimental spatial luminescence intensity distributions.

A generic depiction of such a mesh 100 in the network model used in embodiments of the present invention is shown in Figure 1. Each node e.g. 104 in the network consists of a constant current source e.g. 106 and a diode e.g. 102. There may be variations in the representation of the diode 102, e.g. as characterized by its ideality factor. The diode 102 may also be represented schematically as consisting of two parallel diodes of different ideality factors. Reference is made to [9], [10] and [11] for a full description of the details of the network model, which has been recognized by the inventors to be capable of being used in the simulation of luminescence in embodiments of the present invention.

The simulation predicts the luminescence intensity distribution in the solar cell plane when the solar cell is subjected to the same applied voltages at the points on the metal cathode and anodes, or the same illumination pattern, as in the experimental conditions during the luminescence intensity distribution measurement. The simulated electroluminescence intensity distribution is a function of the contact resistance ρ_C , metal electrode grid line resistance ρ_{finger} , solar cell layers sheet resistance ρ_{sheet} , and diode recombination current densities and their spatial distributions, which can be described using 6 parameters (J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$), making a total of 9 parameters. In one embodiment, auxiliary experiments using the four point probe (which deduces ρ_{sheet}) and busbar-to-busbar measurements (which deduces ρ_{finger}) first reduce the free parameters from 9 to 7. Next, the remaining 7 free parameters (J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$, ρ_C) are varied in a computer finite-element model construction of the solar cell, which is used to simulate both the electroluminescence intensity distribution (when an electrical bias to the solar cell at the suitable points on the metal cathode and anodes is applied), and the photoluminescence intensity distribution (when the cell is in open-circuit conditions and is full area illuminated). The simulated distributions are compared to the corresponding experimentally captured images, in an iterative manner that seeks to minimize the difference between the simulated and experimental spatial luminescence intensity distributions. When the convergence criteria are met, then the 7 free parameters (J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$, ρ_C) are deemed to be parameters of best fit, and the contact resistance is determined simultaneously as the diode recombination current densities.

Next, a first embodiment will be described which can e.g. be applied to a silicon wafer solar cell 200 with an H-pattern front electrode grid as shown in Figure 2a. Figure 3 shows a flow chart 300 of the first embodiment.

Figure 2b shows a finite-element model (FEM) 202 of the H-pattern front electrode grid solar cell of Figure 2a, which is the implementation of the network representation in this example

embodiment. Presently the FEM model is done using Griddler, a software which has been described in [9], [10] and [11], which has been recognized by the inventors to be capable of being used in the simulation of luminescence in embodiments of the present invention.

Briefly, the FEM construction divides the solar cell plane into about 80,000 nodes and 160,000 triangular elements as shown in Figure 2b. Three kinds of triangular elements are defined: 1) emitter region triangles 204, 2) metal region triangles 206, 3) peripheral region triangles 208 (those triangles within 2 mm of the wafer edge). Two kinds of nodes are defined: 1) edge nodes 210 (those which trace the wafer edge) and 2) face nodes 212 (those which do not trace the wafer edge). Each node i is a vertex to a number of triangular elements called bounding triangles. Each node contains a current source and two diode components, such that the current I emanating from the node is given by $I = J_L \times A_{opt} - (J_{01} \times A_{node} + J_{01metal} \times A_{metal} + J_{01peripheral} \times A_{peripheral} + J_{01edge} \times L_{edge}) (\exp(V/V_T) - 1) - (J_{02} \times A_{node} + J_{02metal} \times A_{metal}) (\exp(V/2/V_T) - 1)$

where J_L is the photogenerated current density; A_{opt} is the node optical area, defined as a third of the sum of areas of bounding triangles which are not in the metal region; A_{node} is the node area, defined as a third of the sum of areas of bounding triangles; A_{metal} is the metal area, defined as a third of the sum of areas of bounding triangles which are in the metal region; $A_{peripheral}$ is the peripheral area, defined as a third of the sum of areas of bounding triangles which are in the peripheral region; L_{edge} is the edge length, defined for edge nodes to be the mean distance to neighboring edge nodes. V is the node voltage, and V_T is the thermal voltage which is equal to 25.68 mV at room temperature. J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$ are saturation recombination current densities which influences the voltage distribution in the cell.

Referring to Figure 2b still, adjacent nodes in each triangular element are connected by resistors (compare e.g. 112 in Figure 1). The value of the resistor between two nodes reflects the sheet resistance of the region (the metal region has a sheet resistance $\rho_{metal} = \rho_{finger} w$, where w is the metal finger width; the peripheral and emitter regions are assumed to have identical sheet resistance ρ_{sheet}). The value of the resistor is also determined from the shapes of the nodes' common bounding triangles. The exact calculation of the resistor values follows from the Galerkin method in the field of finite-element methods, which is understood by a person skilled in the art and need not be elaborated upon here.

Referring to Figure 2b still, the points which have a bounding triangle in the metal region (such as the node 214) are called contact node pairs. Each of these points consists of two overlapping nodes, one which takes on a voltage in the semiconductor, and one which takes on a voltage in the metal layer. The two nodes in a contact node pair are connected by a resistor $R_C = \rho_C \times A_{contact}$, where ρ_C is the contact resistance in question and $A_{contact}$ is the effective contact area of the contact node pair. The effective contact area $A_{contact}$ is less than the node area, and is a function of ρ_C and ρ_{sheet} . $A_{contact}$ is calculated using a two-dimensional network method similar to the well-known transmission line method [1] understood by the person skilled in the art, and need not be elaborated upon here.

The flow chart 300 of Figure 3 describes a series of experiments involving mostly luminescence imaging and electrical probing, and also auxiliary experiments like four point probing of non-metallized samples, 302, and busbar-to-busbar resistance measurements, 304, which when combined with simulations using the FEM model, allows the parameters J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$, ρ_C , ρ_{sheet} , ρ_{finger} to be resolved in the example embodiment.

Referring to the right side of Figure 3, the auxiliary routine measurements four point probe, 302, and busbar-to-busbar resistance measurements, 304, allow ρ_{sheet} , ρ_{finger} to be determined, which are fed into the model calculation together with initial values of J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$ and ρ_C , 306. Four point probe measurements are routinely performed on as-diffused wafers before metallization in the production line [1]. Busbar-to-busbar resistance measurement can be easily integrated [2]. The exact nature of the auxiliary measurements need not be elaborated upon here.

Referring to the left side of Figure 3, the luminescence imaging and electrical probing setup forms the main experimental component of this embodiment. Figure 4 shows a schematic drawing illustrating the setup 400 for the H-pattern front electrode grid solar cell 402, for which the front grid consists of a number of busbars e.g. 404 and narrow metal fingers e.g. 406 running perpendicular to the busbars e.g. 404. The setup includes a monochromatic light source 408 which can be a laser or light-emitting diode (LED), of wavelength preferably less than 1000nm, e.g. about 808 or about 915nm, capable of illuminating the solar cell 402 plane with variable intensity I_L (in units of Suns); and a filtered camera 410 capable of rejecting the illuminating light and accepting the emitted luminescence radiation from band-to-band recombination in the silicon wafer of the solar cell 402 [3]. The solar cell 402 is mounted on a temperature controlled metal chuck that regulates its temperature at 25°C in this embodiment. If the solar cell 402 has a full area rear metal electrode, then the chuck metal surface makes a full area electrode contact to the solar cell 402 rear. If the solar cell 402 has an H pattern rear metal electrode, then the chuck may render either full area rear electrical contact, or electrical contact only at the cell 402 rear busbars. At the front, there is a narrow probe bar e.g. 409 with multiple spring loaded probes which make contact to each busbar e.g. 404 on the solar cell 402 H pattern. There are two types of spring loaded probes on each probe bar e.g. 409: current sourcing and voltage sensing probes. The former supplies or extracts current from the solar cell while the latter senses the voltage on the busbar with high input resistance typically exceeding 100kΩ. The current sourcing probes are closely spaced such that the probe bar has the ability to render uniform voltage on the entire busbar.

In this example embodiment, the electrical lines connecting to the current sourcing probes and the voltage sensing probes, are individually controlled and addressed for each busbar, instead of the lines for all current sourcing probes be connected together without distinction of the busbar, and the lines for all voltage sensing probes be connected together without distinction of the busbar. This configuration in this example embodiment advantageously allows for three measurements: 1) single-busbar biased electroluminescence (EL) imaging, to be described below; 2) single busbar open-circuit voltage $V_{OC,BBj}$ under illumination; 3) the auxiliary busbar-to-busbar resistance measurement, already described above. The

configuration can for example be accomplished using a digital switch card 411 that routes the desired current sourcing lines and voltage sensing lines to the source-meter unit 412.

Using the setup of Figure 4, three types of luminescence imaging and probing are performed in the example embodiment: Returning to Figure 3, an imaging configuration for single-busbar biased electroluminescence (EL) imaging, 308, with zero illumination intensity from the light source 408 (Figure 4), $I_L = 0$, and only one probe bar sources current to the solar cell while the other probe bars have floating voltage. This injected current enters the solar cell from one busbar only, spreading into the entire cell plane to create a distinct voltage distribution and electroluminescence intensity distribution (x,y) . The injected current is typically a sizeable fraction of the solar cell's short-circuit current under 1-Sun illumination, chosen at 5A for an example solar cell that has about 9A short-circuit current, in this example embodiment. This process of sourcing current through individual probe bars, is repeated for each busbar on the solar cell. One EL image is taken for each busbar that is biased. Single-busbar biased EL images have intensity distributions that capture the current injected into the busbar and distributed to the entire cell plane via the H pattern. Because the current flow pattern takes the "path of least differential resistance", it is sensitive to ρ_{finger} , $\rho_{emitter}$ and ρ_C , therefore advantageously making the single-busbar biased EL images very useful towards extracting these resistance parameters. To preferably ensure unambiguous determination, the example embodiment optionally uses the auxiliary measurements 302, 304 to determine ρ_{finger} , $\rho_{emitter}$ independently, such that ρ_C can be more easily delineated. In a production environment where ρ_{finger} , $\rho_{emitter}$ may be stable quantities with little variation from cell to cell, it may suffice to update the values of ρ_{finger} , $\rho_{emitter}$ sparingly by means of offline measurements.

The other two types of luminescence imaging and probing in this embodiment are a series of open-circuit photoluminescence (PL) images (x,y) at various light intensities, 310, in this example embodiment being 3.4, 2, 1, 0.3, 0.1, 0.03 Suns, and a short-circuit luminescence image (x,y) at 1 Sun in this example embodiment, 312. The open-circuit PL images, 310, are sensitive to J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$. There is no strict requirement on the number of light intensities used for the open-circuit luminescence images, and as few as two intensities (e.g. 3.4 Suns and 0.1 Suns) will suffice. In addition, the simultaneous capturing of these images (x,y) , (x,y) , and probing of the open-circuit busbar voltages $V_{OC,BBj}$, provides a method (understood by a person skilled in the art) to convert the luminescence intensity under any biasing or illumination conditions to voltage V, 314. One method to do this is described in [4] and is summarized in the flow chart 300, and will not be repeated here.

For each single-busbar bias EL image and each open-circuit PL image, the average value of the luminescence intensity is determined for a predefined set of regions of interest (ROI), as shown in Figure 5. Then the averaged values are converted to voltage $V_{ROI,i}$ where i denotes the index of the ROI, i.e. one average voltage is determined for each rectangular area e.g. 501.

In this embodiment, the regions of interest (ROI) used to describe the voltage variations along the cell plane and shown in Figure 5 are a) adjacent the left busbar in the left busbar single-busbar biased image 502, b) adjacent the middle busbar in the middle busbar single-busbar biased image 504, c) adjacent the right busbar in the right busbar single-busbar biased image 506, d) adjacent the left, middle and right busbars in the open-circuit photoluminescence images 508.

Referring to Figure 3, for the FEM simulation, some initial values of ρ_C , J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$, , 306, along with the measured ρ_{sheet} , ρ_{finger} , 302, 304, are fed into the FEM simulator 316. The FEM simulator 316 solves the cell voltage distribution at each of the three single-busbar biasing conditions, 318, and each of the 6 open-circuit PL conditions, 320. The simulated cell voltage is converted to luminescence intensity and the average value of the simulated luminescence intensity is calculated for the same predefined set of regions of interest (ROI) as in Figure 5, and the averaged values are converted to voltage $V_{ROI,i,sim}$ where i denotes the index of the ROI, 322. For the open-circuit PL condition, the simulated voltages of each busbar $V_{oc,BBj,sim}$ are also recorded.

Referring to Figure 3, an iterative procedure follows in which the simulated $V_{ROI,i,sim}$ is compared to the measured $V_{ROI,i}$, 323, for each simulated image and ROI, and the simulated $V_{oc,BBj,sim}$ is compared to the measured $V_{oc,BBj}$, 325, for each open-circuit PL image and busbar, 324. A root mean square error is obtained from the differences of each simulation-experimental result pair, as prescribed in the flow chart of Figure 3, and the values of ρ_C , J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$ are adjusted, 326, until the root mean square error falls below a certain threshold that signals convergence, 328. When the convergence criteria are met, then the 7 free parameters (J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$, ρ_C) are deemed to be parameters of best fit and output/reported, 330, and the contact resistance is determined simultaneously as the diode recombination current densities.

Figure 6 compares the experimental luminescence images 601-604 to the simulated images 605-608, for an example three-busbar silicon wafer solar cell at three different single busbar biasing and open circuit conditions, and showing good agreement. The values of J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$, ρ_C correspond to best fit conditions.

Table 1 compares the contact resistance ρ_C determined using the present invention and the traditional transmission line method (TLM) [1], for three silicon wafer solar cells. Each solar cell has a three-busbar H pattern front electrode grid. The solar cells are intentionally made to have different values of ρ_C by subjecting them to different contact firing temperatures.

Table 1. Comparison of the contact resistance ρ_C determined using the present invention and the traditional transmission line method (TLM), for three silicon wafer solar cells.

	Determined ρ_C (in units of $\text{m}\Omega\text{-cm}^2$)	
	Example Embodiment	Transmission Line Method (TLM, conventional method [1])
Solar Cell 1	5.49	4.21
Solar Cell 2	7.24	6.30
Solar Cell 3	13.20	9.05

In the following, a second embodiment will be described which is also applied to a silicon wafer solar cell with an H-pattern front electrode grid as shown in Figure 2a.

The methodology of this embodiment is similar to the embodiment described above with reference to Figures 3 to 6: The main difference is that the lateral current flow and the resultant luminescence pattern being analyzed, are created using a different arrangement. In this embodiment, as shown in Figure 8, a highly non-uniform light source is used to induce current in a select area of the cell 802. Preferably, non-uniform light source in the form of a line light source 804 casts light in the form of a tight line of <1cm in width, on the cell 802 surface. Preferably, the line light source 804 is powerful enough to induce up to three times the short-circuit current the cell 802 would generate under 1-Sun uniform illumination. Electrical contact is not essential, but may be used to measure accurately the current that the line light source generates under short-circuit conditions. The setup 800 for the H-pattern front electrode grid solar cell 802, for which the front grid consists of a number of busbars e.g. 805 and narrow metal fingers e.g. 806 running perpendicular to the busbars e.g. 805. The setup also includes a monochromatic light source 808 which can be a laser or light-emitting diode (LED), of wavelength preferably less than 1000nm, capable of illuminating the solar cell 802 plane with variable intensity I_L (in units of Suns); and a filtered camera 810 capable of rejecting the illuminating light and accepting the emitted luminescence radiation from band-to-band recombination in the silicon wafer of the solar cell 802 [3]. The configuration can for example be accomplished using a digital switch card 811 that routes the desired current sourcing lines and, if desired, voltage sensing lines from front electrode contacts/probes e.g. 807, to the source-meter unit 812.

The line light source of this embodiment performs the same function as the single busbar biasing in the first embodiment described above -- it creates a well-defined lateral current flow in the direction of the metal fingers, in this embodiment for photoluminescence imaging in open circuit, 708, as shown in Figure 7. The line light source creates a light induced current I_L in the cell, which can be determined by biasing the cell to short-circuit current

conditions and then measuring the short-circuit current, as described in 708 of Figure 7. This light induced current I_L can then be used as a known input in the finite-element simulation of the voltage distribution 718. There is no strict requirement on the number of different line light positions for which for photoluminescence imaging in open circuit is performed, and as few as two positions (e.g. compare Figure s 9(a) and (b)) will suffice. As in the first embodiment, the other two types of luminescence imaging and probing are a series of open-circuit photoluminescence (PL) images (x,y) at various light intensities, 710, in this example being 3.4, 2, 1, 0.3, 0.1, 0.03 Suns, and a short-circuit luminescence image (x,y) at 1 Sun, 712. In addition, the simultaneous capturing of these images and probing, using the front electrode contacts/probes e.g. 807 (Figure 8), of the open-circuit busbar voltages $V_{OC,BBj}$, provides a method (understood by a person skilled in the art) to convert the luminescence intensity under any biasing or illumination conditions to voltage V , 714. One method to do this is described in [4] and is summarized in the flow chart 700, and will not be repeated here. For each luminescence image, the average value of the luminescence intensity is determined for a predefined set of regions of interest (ROI), as shown in Figure 9, which are a) the region between the middle and right busbars in the photoluminescence image 902, b) the region between the left and middle busbars in the photoluminescence image 904, and a) the regions between the left and the middle busbars, between the middle and the right busbars, adjacent left of the left busbar and adjacent right of the right busbar in photoluminescence image 906. Then the averaged values are converted to voltage $V_{ROI,i}$ where i denotes the index of the ROI, i.e. one average voltage is determined for each rectangular area e.g. 901. Then, the routine of iterative solving for ρ_C , J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$ proceeds according to Figure 7, in a similar manner described above for the first embodiment.

Referring to Figure 7, for the FEM simulation, some initial values of ρ_C , J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$, 706, along with the measured ρ_{sheet} , ρ_{finger} , 702, 704, are fed into the FEM simulator 716. The FEM simulator 716 solves the cell voltage distribution at each of the line light source conditions, 718, and each of the 6 open-circuit PL conditions, 720. The simulated cell voltage is converted to luminescence intensity and the average value of the simulated luminescence intensity is calculated for the same predefined set of regions of interest (ROI) as in Figure 9, and the averaged values are converted to voltage $V_{ROI,i,sim}$ where i denotes the index of the ROI, 722. For the open-circuit PL condition, the simulated voltages of each busbar $V_{oc,BBj,sim}$ are also recorded.

Referring to Figure 7, an iterative procedure follows in which the simulated $V_{ROI,i,sim}$ is compared to the measured $V_{ROI,i}$, 723, for each simulated image and ROI, and the simulated $V_{oc,BBj,sim}$ is compared to the measured $V_{oc,BBj}$, 725, for each open-circuit PL image and line light measurement, 724. A root mean square error is obtained from the differences of each simulation-experimental result pair, as prescribed in the flow chart of Figure 7, and the values of ρ_C , J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$ are adjusted, 726, until the root mean square error falls below a certain threshold that signals convergence, 728. When the convergence criteria are met, then the 7 free parameters (J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$, ρ_C) are

deemed to be parameters of best fit and output/reported, 730, and the contact resistance is determined simultaneously as the diode recombination current densities.

In modifications of the first and second embodiment, the series of open-circuit photoluminescence (PL) images at different light intensities, 310, 710, can be replaced with another set of luminescence images. For example, Glatthaar has proposed a four image algorithm to determine the spatial function of the saturation current density J_0 , in which only one image is taken at open-circuit conditions, the other three images being taken with illumination and current extraction simultaneously [4]. If this so-called Glatthaar method is adopted, then the recombination parameters of the solar cell is no longer defined by the set J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$, but rather, a spatially dependent variable $J_0(x,y)$. [4] describes a method to determine $J_0(x,y)$, from the four luminescence images, which can then be used as the initial value of $J_0(x,y)$ in the iterative simulation and fitting procedure, in modified embodiments of the present invention.

It is also possible that once the FEM simulations have been applied to enough samples, that an empirical or statistical law can be deduced whereby the luminescence images need not be fitted by FEM simulations, but rather the contact resistance ρ_C can be deduced directly from some simple property of the luminescence pattern. For example, in the first embodiment, in the single-busbar biased EL images shown in Figure 6, the EL intensity decays away from the busbar to which current is injected. The decay is sharper for samples with lower ρ_C and conversely so for samples with higher ρ_C . Moreover, the EL intensity $\Phi(x,y)$ can be roughly fitted to mathematical functions such as $\Phi(x,y) = A \exp(-x/L_T) + B \exp(x/L_T)$, where x is the distance from the biased busbar in the direction of the fingers and perpendicular to the busbar, A , B , L_T are fitting parameters. There can be an empirical or analytical law relating L_T to the parameters ρ_C , ρ_{finger} , ρ_{sheet} , J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$. in modified versions of the first embodiment.

As another example, in the second embodiment, again luminescence intensity $\Phi(x,y)$ can be roughly fitted to mathematical functions such as $\Phi(x,y) = A \exp(-x/L_T) + B \exp(x/L_T)$, where x is the distance from the biased busbar in the direction of the fingers and perpendicular to the busbar. A , B , L_T are fitting parameters. It was found that, provided J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, are not highly spatially non-uniform, L_T is rather weakly dependent on the particular values of J_{01} , J_{02} , $J_{01metal}$, $J_{02metal}$, J_{01edge} , $J_{01peripheral}$, but strongly dependent on ρ_C , ρ_{finger} , ρ_{sheet} . Therefore, if ρ_{finger} , ρ_{sheet} are known by other independent measurements, ρ_C can be inferred accurately from empirical fits of L_T provided that the solar cells in the production line do not have drastically different recombination parameters. A notable advantage of empirically fitting the luminescence pattern in a modification of the second embodiment is that it requires then no measurement of the cell voltage or current, and thus advantageously eliminates the need for electrical contacting, making this modification of the second embodiment a contactless technique. This modified embodiment can for example be used to determine the contact resistance of cells encapsulated inside a PV module.

If embodiments of the present invention are applied to a solar cell has a full area rear metal electrode, then the chuck metal surface makes a full area electrode contact to the solar cell rear. If the solar cell has an H pattern rear metal electrode, then the chuck may render either full area rear electrical contact, or electrical contact only at the cell rear busbars. In the latter case, then it is also possible to individually control and address the current and voltage on the rear busbars, as in the front side. The single-busbar biasing in this case then involves not only defining the busbar on the front electrode grid to bias, but also the busbar on the rear electrode grid to apply the ground voltage.

Figure 10 shows a flowchart 1000 illustrating a method for determining the contact resistance of a solar cell having a front electrode grid on a front surface thereof, the method comprising the steps of (1002) capturing one or more luminescence images of the front surface of the solar cell; (1004) determining a measured luminescence distribution in a cell plane comprising the front surface of the solar cell based on the one or more luminescence images; (1006) identifying a simulated luminescence distribution which meets a similarity criterion to the measured luminescence distribution; and (1008) determining a quantitative value for the contact resistance from the simulated luminescence distribution that meets the similarity criterion.

Identifying the simulated luminescence distribution which meets a similarity criterion to the measured luminescence distribution may comprise:

fitting the simulated luminescence distributions to the measured luminescence distribution such that a convergence criterion is met;

and determining the quantitative value for the contact resistance from the simulated luminescence distribution that meets the similarity criterion may comprise:

determining the contact resistance from the fitted simulated luminescence distribution that meets the convergence criterion.

The method may comprise using a finite-element model for the cell plane. The finite-element model may describe the cell plane as a multitude of diodes interconnected by resistors. The method may comprise using a mathematical function describing the luminescence distribution. The mathematical function may describe the luminescence distribution as a function of at least one coordinate in the cell plane. The coordinate may comprise a distance from a busbar of the front electrode grid in a direction of fingers of the front electrode grid. The method may further comprise performing auxiliary measurements to determine measured values for a sheet resistance of the solar cell and a finger resistance of the front electrode.

Identifying the simulated luminescence distribution which meets the similarity criterion to the measured luminescence distribution and determining the quantitative value for the contact resistance from the simulated luminescence distribution that meets the similarity criterion may comprise:

identifying one or more characteristics of the measured luminescence distribution; and

determining as the quantitative value for the contact resistance a contact resistance value associated with the simulated luminescence distribution that meets the similarity criterion based on the one or more characteristics.

- 5 Capturing one or more luminescence images of the front surface of the solar cell may comprise measuring a single busbar biased electroluminescence distribution for each busbar of the front electrode grid.

The solar cell may comprise a rear electrode grid, and measuring the one or more single busbar biased electroluminescence distributions comprises biasing corresponding single busbars of the front and rear electrode grids.

- 10 Capturing one or more luminescence images of the front surface of the solar cell may comprise:

measuring two or more photoluminescence distributions induced by exposure to a non-uniform, relative to the cell plane, light source at different respective positions relative to the cell plane.

- 15 The non-uniform light source may comprise a line light source. The method may further comprise biasing the solar cell to short-circuit current conditions and measuring the short-circuit current for each exposure to the non-uniform light source.

Capturing one or more luminescence images of the front surface of the solar cell may comprise:

- 20 measuring one or more open-circuit photoluminescence distributions at different respective light intensities; and

probing of the open-circuit busbar voltages for each of said one or more measurements.

- 25 Capturing one or more luminescence images of the front surface of the solar cell may comprise measuring two or more short-circuit photoluminescence distributions under different predetermined light intensities. The predetermined light intensity may be one Sun.

- 30 Figure 11 shows a schematic diagram illustrating a system 1100 for determining the contact resistance of a solar cell having a front electrode grid on a front surface thereof, the system comprising an imaging unit (1102) for capturing one or more luminescence images of the front surface of the solar cell; and a processing unit (1104) for:

determining a measured luminescence distribution in a cell plane comprising the front surface of the solar cell based on the one or more luminescence images;

identifying a simulated luminescence distribution which meets a similarity criterion to the measured luminescence distribution; and

determining a quantitative value for the contact resistance from the simulated luminescence distribution that meets the similarity criterion.

Identifying the simulated luminescence distribution which meets a similarity criterion to the measured luminescence distribution may comprise:

5 fitting the simulated luminescence distributions to the measured luminescence distribution such that a convergence criterion is met;

 and determining the quantitative value for the contact resistance from the simulated luminescence distribution that meets the similarity criterion may comprise:

10 determining the contact resistance from the fitted simulated luminescence distribution that meets the convergence criterion.

The processor (1104) may be configured for using a finite-element model for the cell plane. The finite-element model may describe the cell plane as a multitude of diodes interconnected by resistors. The processor (1104) may be configured for using a mathematical function describing the luminescence distribution. The mathematical function may describe the
15 luminescence distribution as a function of at least one coordinate in the cell plane. The coordinate may comprise a distance from a busbar of the front electrode grid in a direction of fingers of the front electrode grid.

The system may further comprise a measurement unit (1106) for performing auxiliary measurements to determine measured values for a sheet resistance of the solar cell and a
20 finger resistance of the front electrode.

Identifying the simulated luminescence distribution which meets the similarity criterion to the measured luminescence distribution and determining the quantitative value for the contact resistance from the simulated luminescence distribution that meets the similarity criterion may comprise:

25 identifying one or more characteristics of the measured luminescence distribution; and

 determining as the quantitative value for the contact resistance a contact resistance value associated with the simulated luminescence distribution that meets the similarity criterion based on the one or more characteristics.

The imaging unit (1102) may be configured for measuring a single busbar biased electroluminescence distribution for each busbar of the front electrode grid. The solar cell
30 may comprise a rear electrode grid, and the system may be configured for biasing corresponding single busbars of the front and rear electrode grids for the measuring of the one or more single busbar biased electroluminescence distributions.

The imaging unit (1102) may be configured for measuring two or more photoluminescence
35 distributions induced by exposure to a non-uniform, relative to the cell plane, light source at different respective positions relative to the cell plane. The non-uniform light source may

comprise a line light source. The system may further comprise a measurement unit (1108) for biasing the solar cell to short-circuit current conditions and measuring the short-circuit current for each exposure to the non-uniform light source.

The imaging unit (1102) may be configured for measuring one or more open-circuit photoluminescence distributions at different respective light intensities, and the system further comprises a measurement unit (1110) for probing of the open-circuit busbar voltages for each of said one or more measurements.

The imaging unit (1102) may be configured for measuring two or more short-circuit photoluminescence distributions under different predetermined light intensities. The predetermined light intensity may be one Sun.

Embodiments of the present invention can be applied to offline solar cell metrology, inline solar cell metrology, solar cell production line process control. The modified second embodiment described herein can be implemented in a contactless manner, and therefore can be used to determine contact resistance in cells encapsulated inside PV modules in the field, where diagnostics of module performance degradation is an important topic.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive. Also, the invention includes any combination of features, in particular any combination of features in the patent claims, even if the feature or combination of features is not explicitly specified in the patent claims or the present embodiments.

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8. Jurgen Carstensen, Andreas Schutt, Helmut Foll, Wilhelm Warta, Martin Kasemann, “Measuring Method and Device for Characterizing a Semiconductor Component”, patent publication number US20110012636,
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9. Johnson Wong, “Griddler: Intelligent Computer Aided Design of Complex Solar Cell Metallization Patterns” Proceedings of the 39th IEEE Photovoltaic Specialists Conference, Tampa, USA (2013).
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CLAIMS

1. A method for determining the contact resistance of a solar cell having a front electrode grid on a front surface thereof, the method comprising the steps of:

capturing one or more luminescence images of the front surface of the solar cell;

5 determining a measured luminescence distribution in a cell plane comprising the front surface of the solar cell based on the one or more luminescence images;

identifying a simulated luminescence distribution which meets a similarity criterion to the measured luminescence distribution; and

10 determining a quantitative value for the contact resistance from the simulated luminescence distribution that meets the similarity criterion.

2. The method of claim 1, wherein identifying the simulated luminescence distribution which meets a similarity criterion to the measured luminescence distribution comprises:

fitting the simulated luminescence distributions to the measured luminescence distribution such that a convergence criterion is met;

15 and wherein determining the quantitative value for the contact resistance from the simulated luminescence distribution that meets the similarity criterion comprises:

determining the contact resistance from the fitted simulated luminescence distribution that meets the convergence criterion.

3. The method of claim 2, comprises using a finite-element model for the cell plane.

20 4. The method of claim 3, wherein the finite-element model describes the cell plane as a multitude of diodes interconnected by resistors.

5. The method of claim 2, comprising using a mathematical function describing the luminescence distribution.

25 6. The method of claim 5, wherein the mathematical function describes the luminescence distribution as a function of at least one coordinate in the cell plane.

7. The method of claim 6, wherein the coordinate comprises a distance from a busbar of the front electrode grid in a direction of fingers of the front electrode grid.

30 8. The method of any one of claims 2 to 7, further comprising performing auxiliary measurements to determine measured values for a sheet resistance of the solar cell and a finger resistance of the front electrode.

9. The method of claim 1, wherein identifying the simulated luminescence distribution which meets the similarity criterion to the measured luminescence distribution and

determining the quantitative value for the contact resistance from the simulated luminescence distribution that meets the similarity criterion comprise:

identifying one or more characteristics of the measured luminescence distribution; and

5 determining as the quantitative value for the contact resistance a contact resistance value associated with the simulated luminescence distribution that meets the similarity criterion based on the one or more characteristics.

10. The method of any one of the preceding claims, wherein capturing one or more luminescence images of the front surface of the solar cell comprises:

10 measuring a single busbar biased electroluminescence distribution for each busbar of the front electrode grid.

11. The method of claim 10, wherein the solar cell comprises a rear electrode grid, and measuring the one or more single busbar biased electroluminescence distributions comprises biasing corresponding single busbars of the front and rear electrode grids.

15 12. The method of any one of claims 1 to 9, wherein capturing one or more luminescence images of the front surface of the solar cell comprises:

measuring two or more photoluminescence distributions induced by exposure to a non-uniform, relative to the cell plane, light source at different respective positions relative to the cell plane.

20 13. The method of claim 12, wherein the non-uniform light source comprises a line light source.

14. The method of claims 12 or 13, further comprising biasing the solar cell to short-circuit current conditions and measuring the short-circuit current for each exposure to the non-uniform light source.

25 15. The method of any one of the preceding claims, wherein capturing one or more luminescence images of the front surface of the solar cell comprises:

measuring one or more open-circuit photoluminescence distributions at different respective light intensities; and

probing of the open-circuit busbar voltages for each of said one or more measurements.

30 16. The method of any one of the preceding claims, wherein capturing one or more luminescence images of the front surface of the solar cell comprises:

measuring two or more short-circuit photoluminescence distributions under different predetermined light intensities.

17. The method of claim 16, wherein the predetermined light intensity is one Sun.

18. A system for determining the contact resistance of a solar cell having a front electrode grid on a front surface thereof, the system comprising:

an imaging unit for capturing one or more luminescence images of the front surface of the solar cell; and

a processing unit for

determining a measured luminescence distribution in a cell plane comprising the front surface of the solar cell based on the one or more luminescence images;

identifying a simulated luminescence distribution which meets a similarity criterion to the measured luminescence distribution; and

determining a quantitative value for the contact resistance from the simulated luminescence distribution that meets the similarity criterion.

19. The system of claim 18, wherein identifying the simulated luminescence distribution which meets a similarity criterion to the measured luminescence distribution comprises:

fitting the simulated luminescence distributions to the measured luminescence distribution such that a convergence criterion is met;

and wherein determining the quantitative value for the contact resistance from the simulated luminescence distribution that meets the similarity criterion comprises:

determining the contact resistance from the fitted simulated luminescence distribution that meets the convergence criterion.

20. The system of claim 19, wherein the processor is configured for using a finite-element model for the cell plane.

21. The system of claim 20, wherein the finite-element model describes the cell plane as a multitude of diodes interconnected by resistors.

22. The system of claim 19, wherein the processor is configured for using a mathematical function describing the luminescence distribution.

23. The system of claim 22, wherein the mathematical function describes the luminescence distribution as a function of at least one coordinate in the cell plane.

24. The system of claim 23, wherein the coordinate comprises a distance from a busbar of the front electrode grid in a direction of fingers of the front electrode grid.

25. The system of any one of claims 18 to 24, further comprising a measurement unit for performing auxiliary measurements to determine measured values for a sheet resistance of the solar cell and a finger resistance of the front electrode.

26. The system of claim 18, wherein identifying the simulated luminescence distribution which meets the similarity criterion to the measured luminescence distribution and determining the quantitative value for the contact resistance from the simulated luminescence distribution that meets the similarity criterion comprise:

- 5 identifying one or more characteristics of the measured luminescence distribution; and
- determining as the quantitative value for the contact resistance a contact resistance value associated with the simulated luminescence distribution that meets the similarity criterion based on the one or more characteristics.

10 27. The system of any one of claims 18 to 26, wherein the imaging unit is configured for measuring a single busbar biased electroluminescence distribution for each busbar of the front electrode grid.

15 28. The system of claim 27, wherein the solar cell comprises a rear electrode grid, and the system is configured for biasing corresponding single busbars of the front and rear electrode grids for the measuring of the one or more single busbar biased electroluminescence distributions.

29. The system of any one of claims 18 to 26, wherein the imaging unit is configured for measuring two or more photoluminescence distributions induced by exposure to a non-uniform, relative to the cell plane, light source at different respective positions relative to the cell plane.

20 30. The system of claim 29, wherein the non-uniform light source comprises a line light source.

31. The system of claims 29 or 30, further comprising a measurement unit for biasing the solar cell to short-circuit current conditions and measuring the short-circuit current for each exposure to the non-uniform light source.

25 32. The system of any one of claims 18 to 31, the imaging unit is configured for measuring one or more open-circuit photoluminescence distributions at different respective light intensities, and the system further comprises a measurement unit for probing of the open-circuit busbar voltages for each of said one or more measurements.

30 33. The system of any one of claims 18 to 32, wherein the imaging unit is configured for measuring two or more short-circuit photoluminescence distributions under different predetermined light intensities.

34. The system of claim 33, wherein the predetermined light intensity is one Sun.

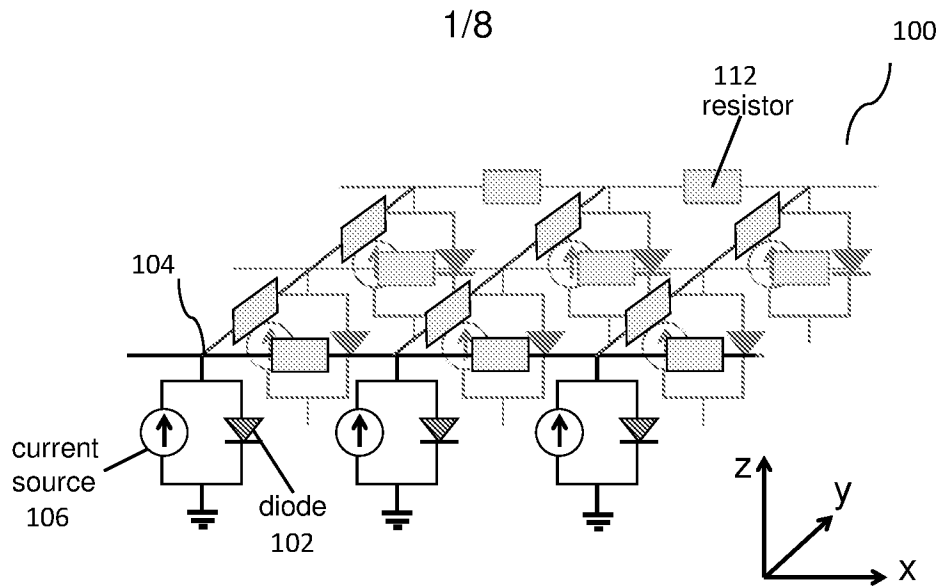


Figure 1

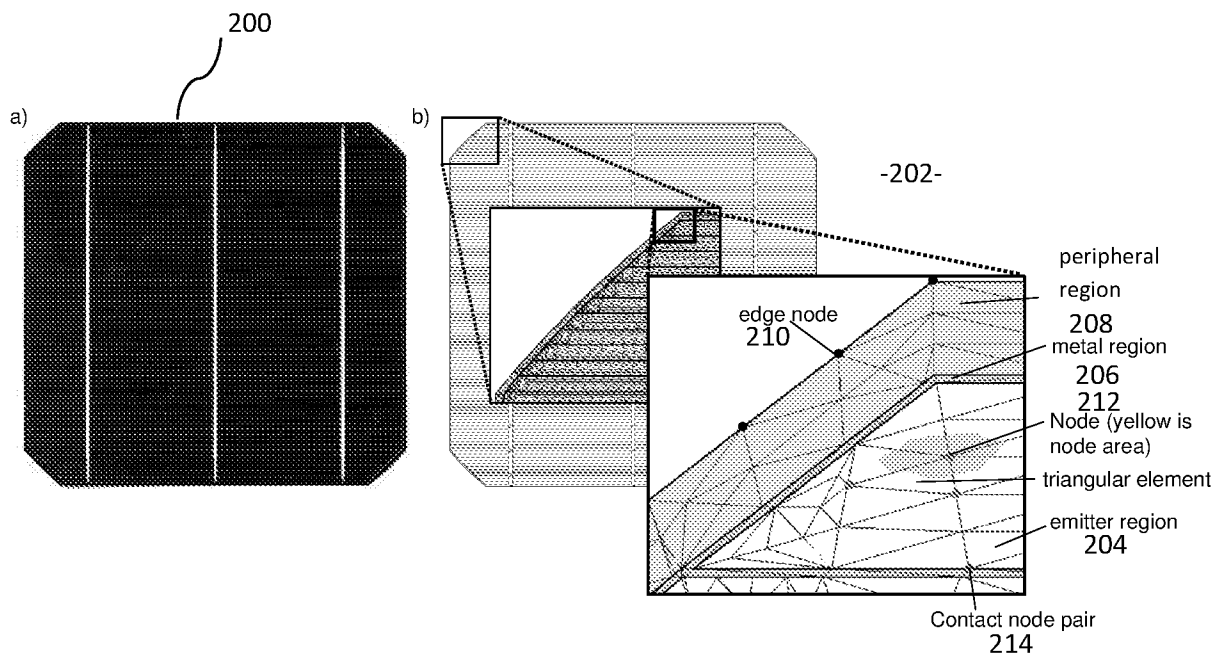


Figure 2.

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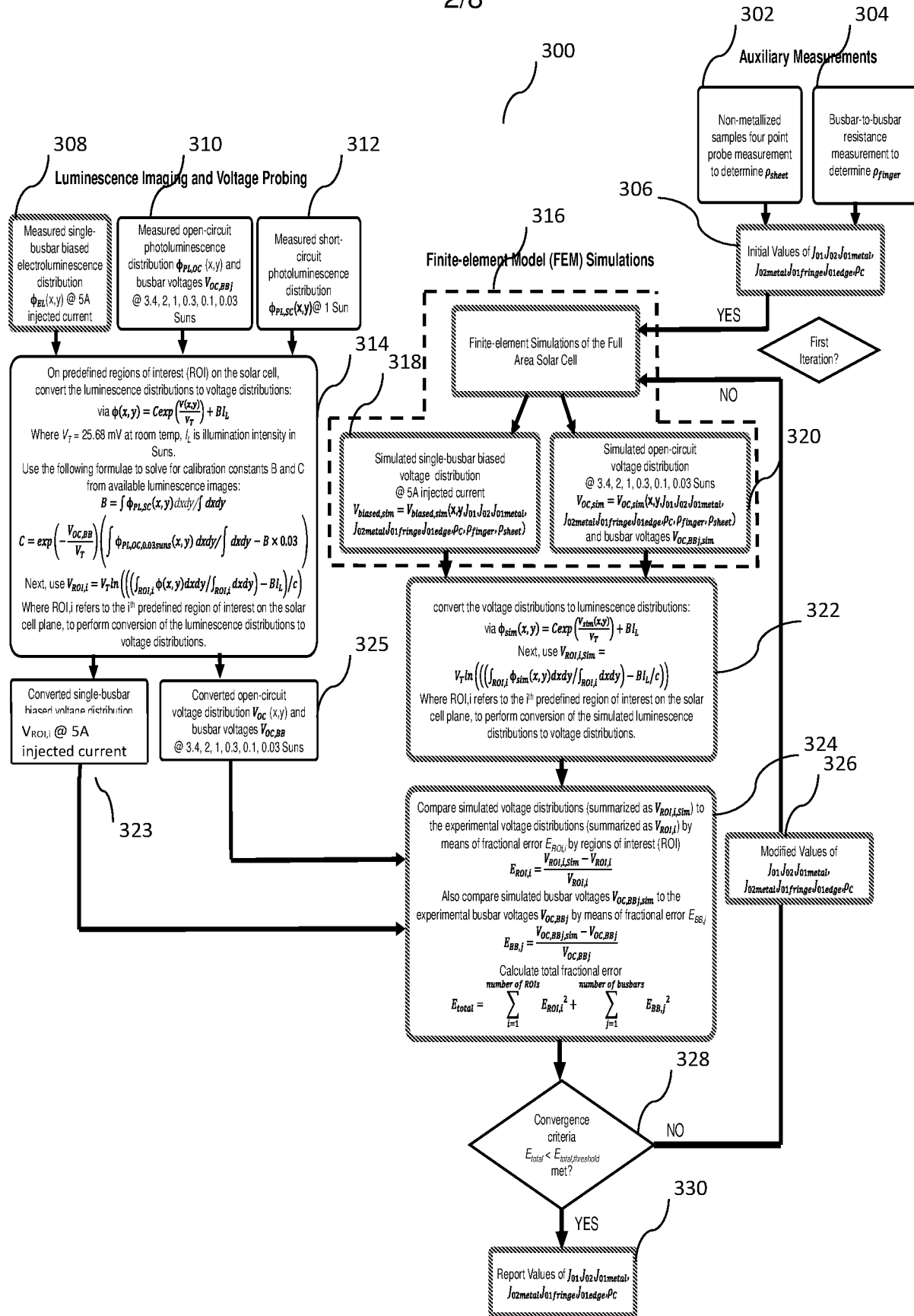


Figure 3

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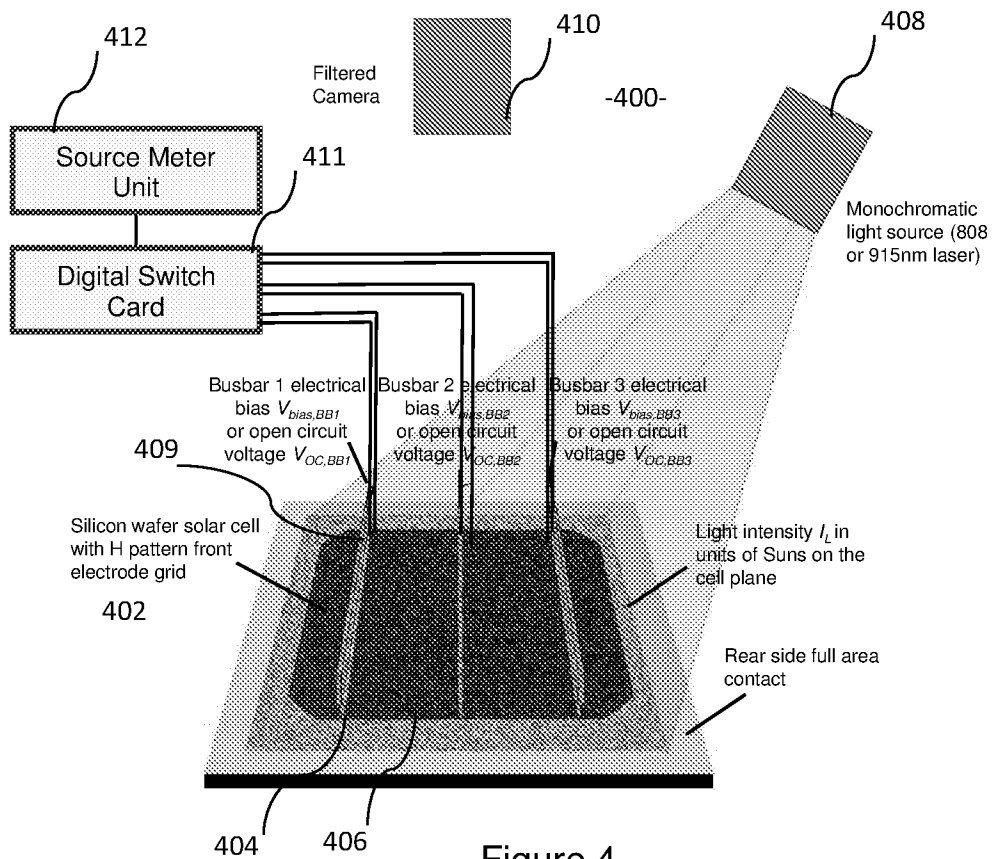


Figure 4

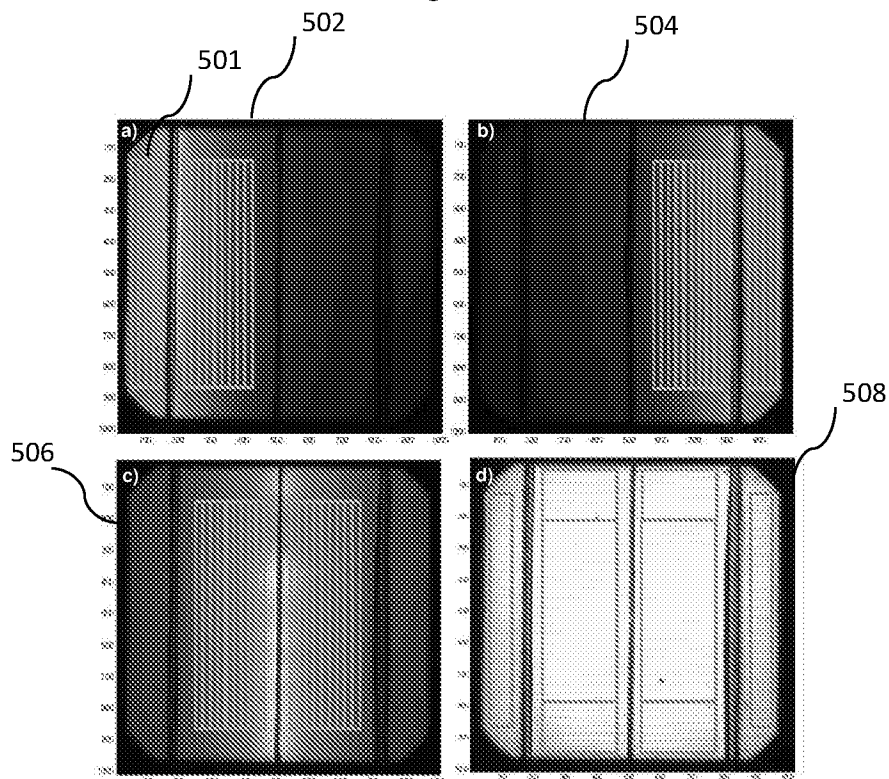


Figure 5.

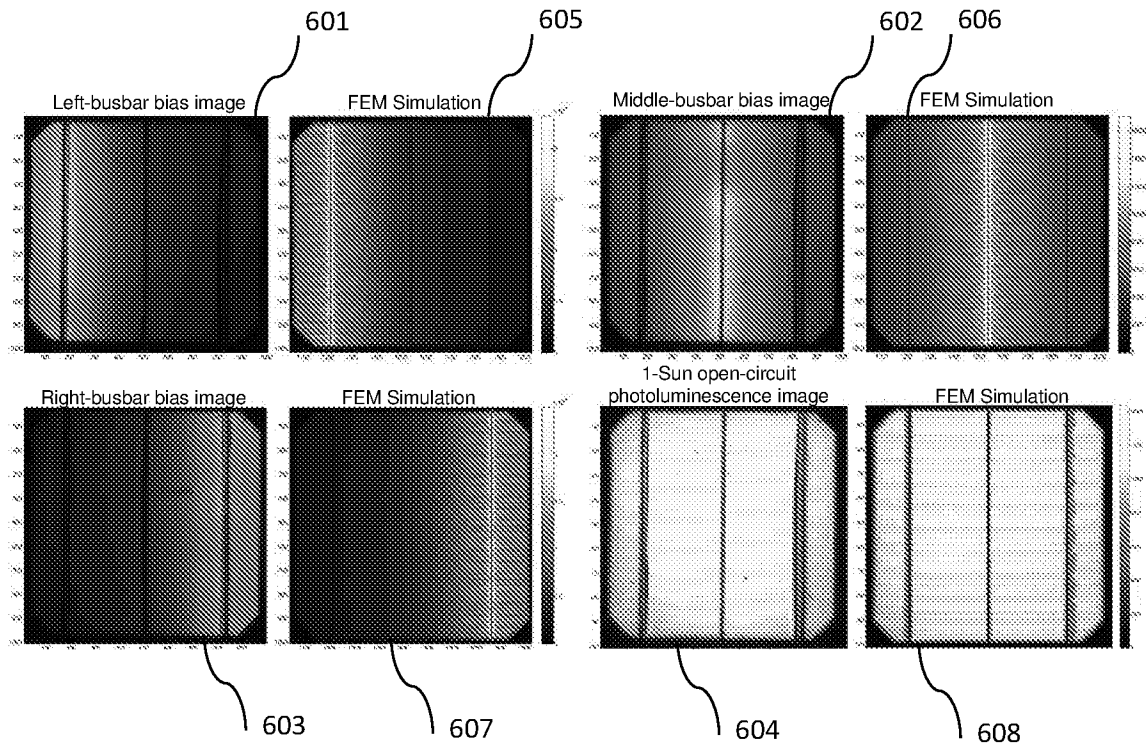


Figure 6

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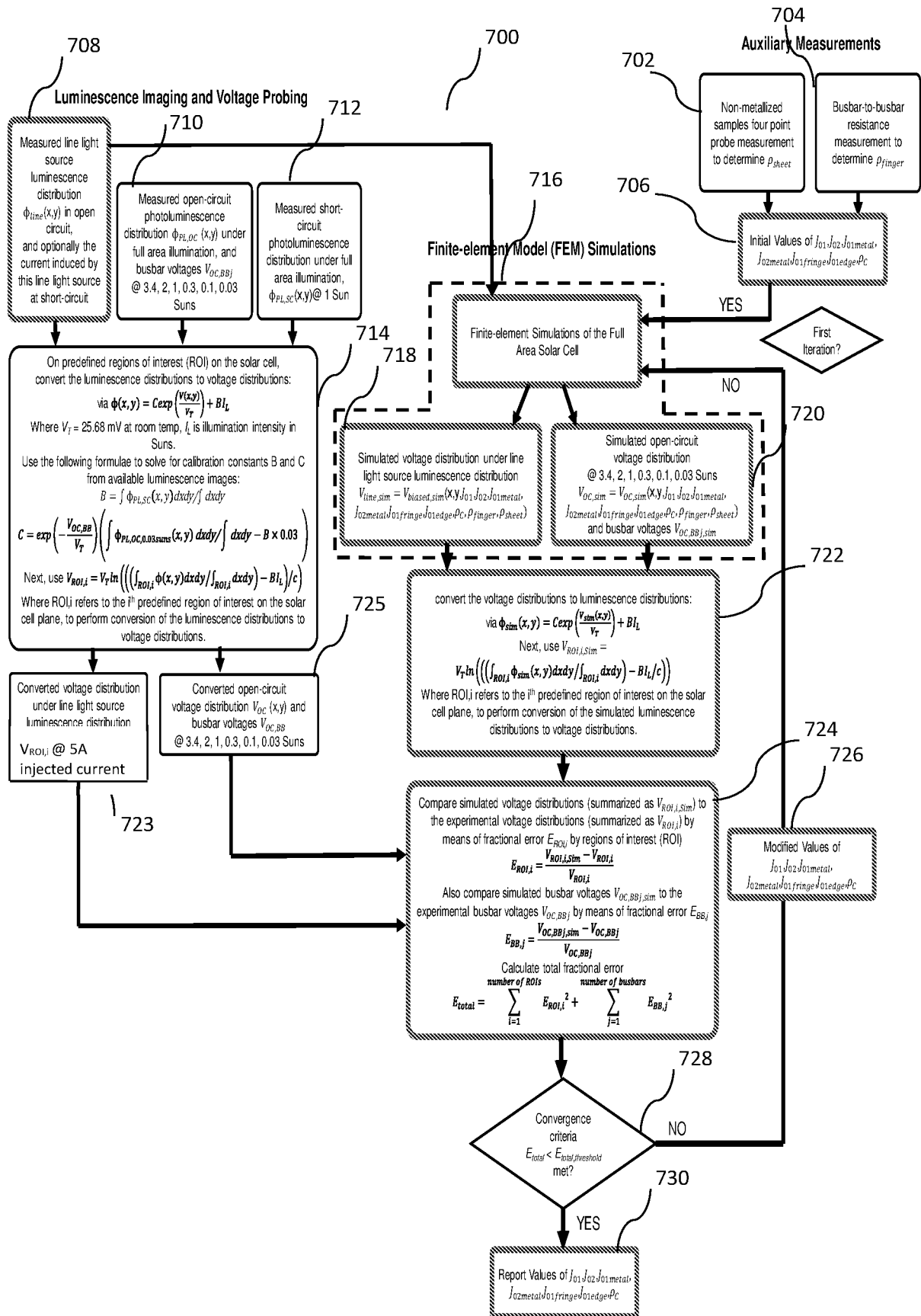


Figure 7

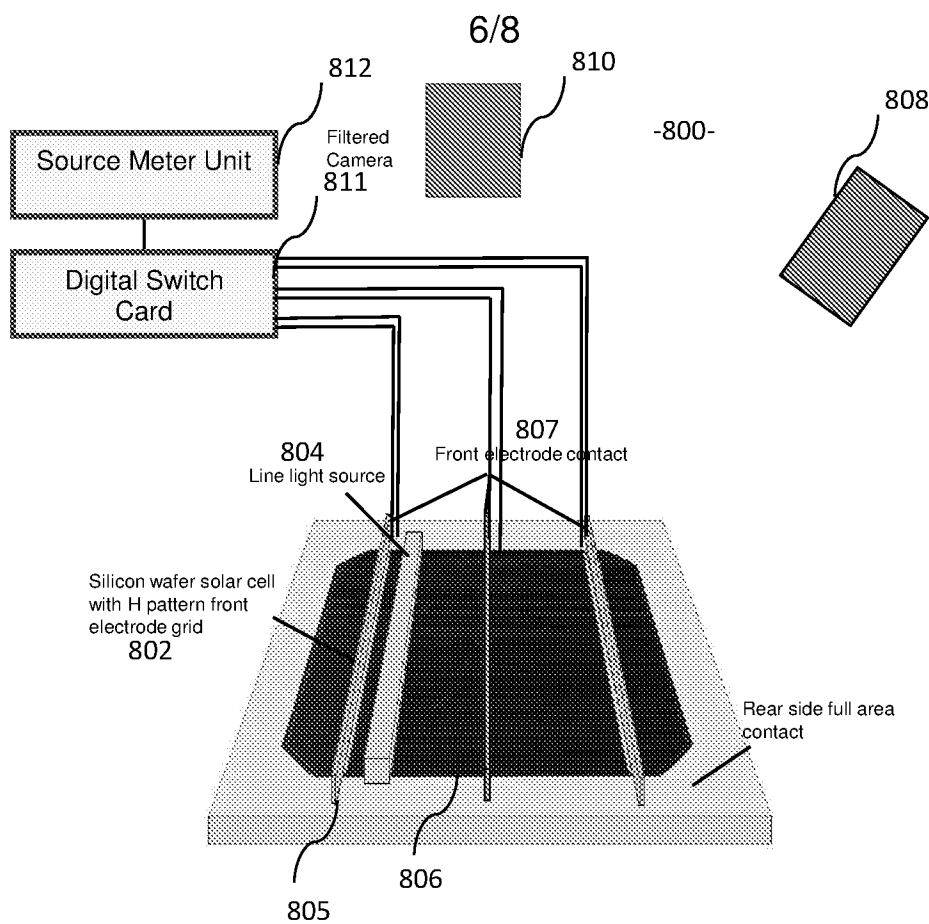


Figure 8

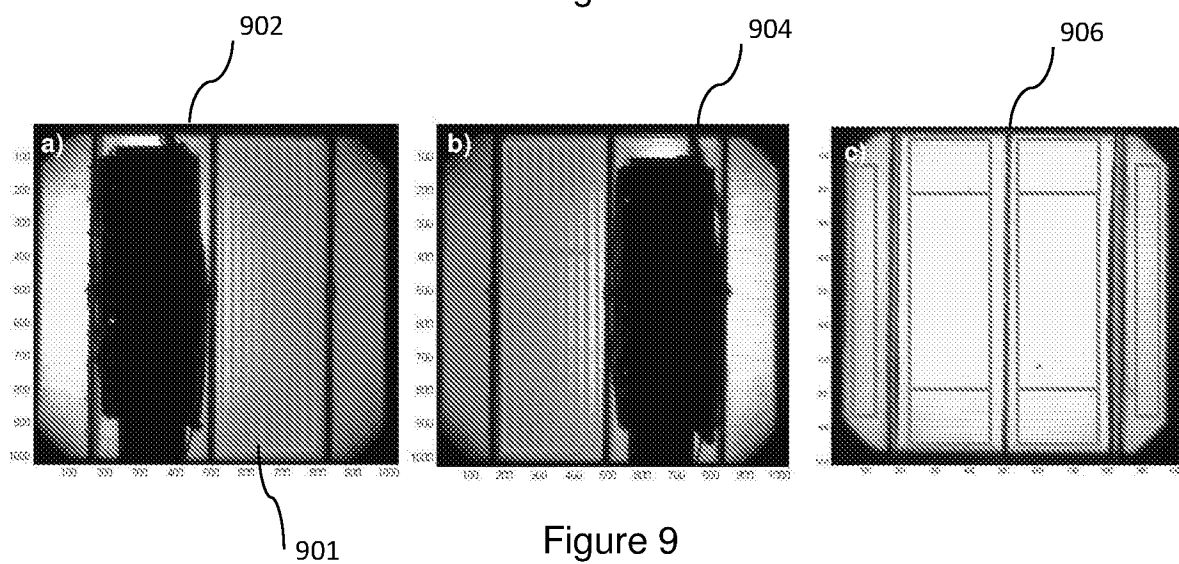


Figure 9

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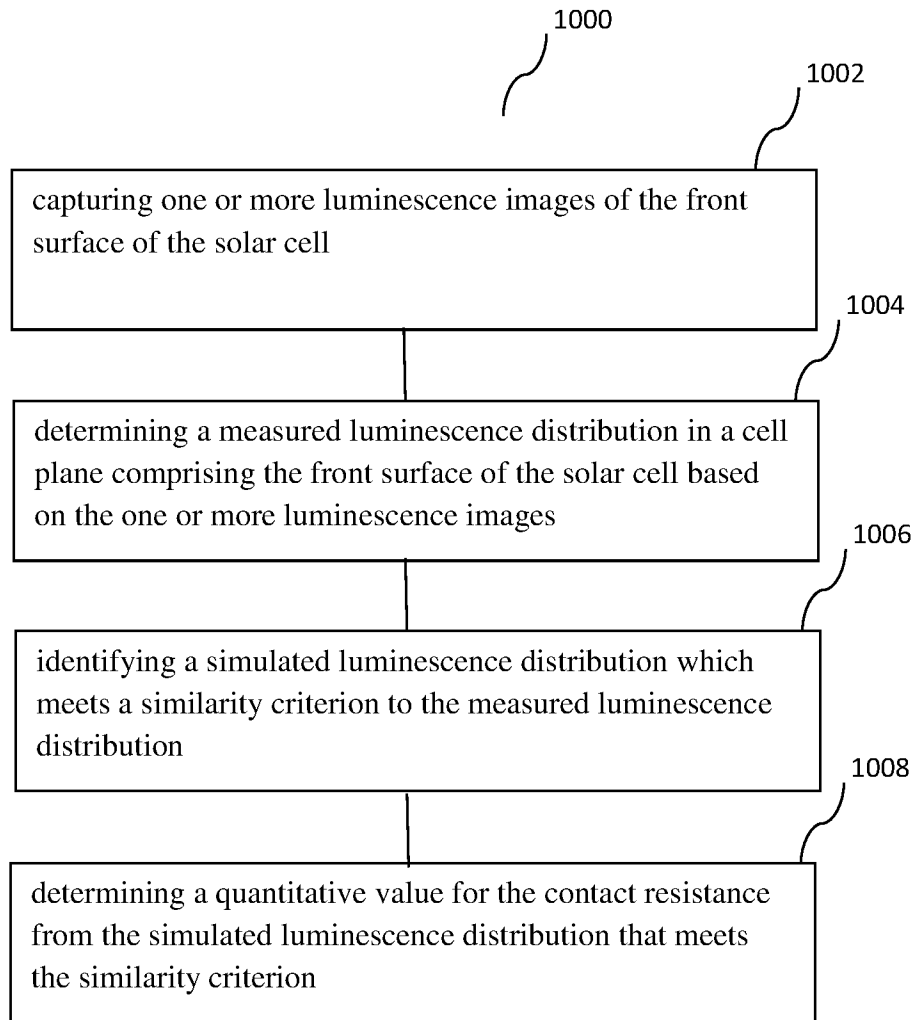


Figure 10

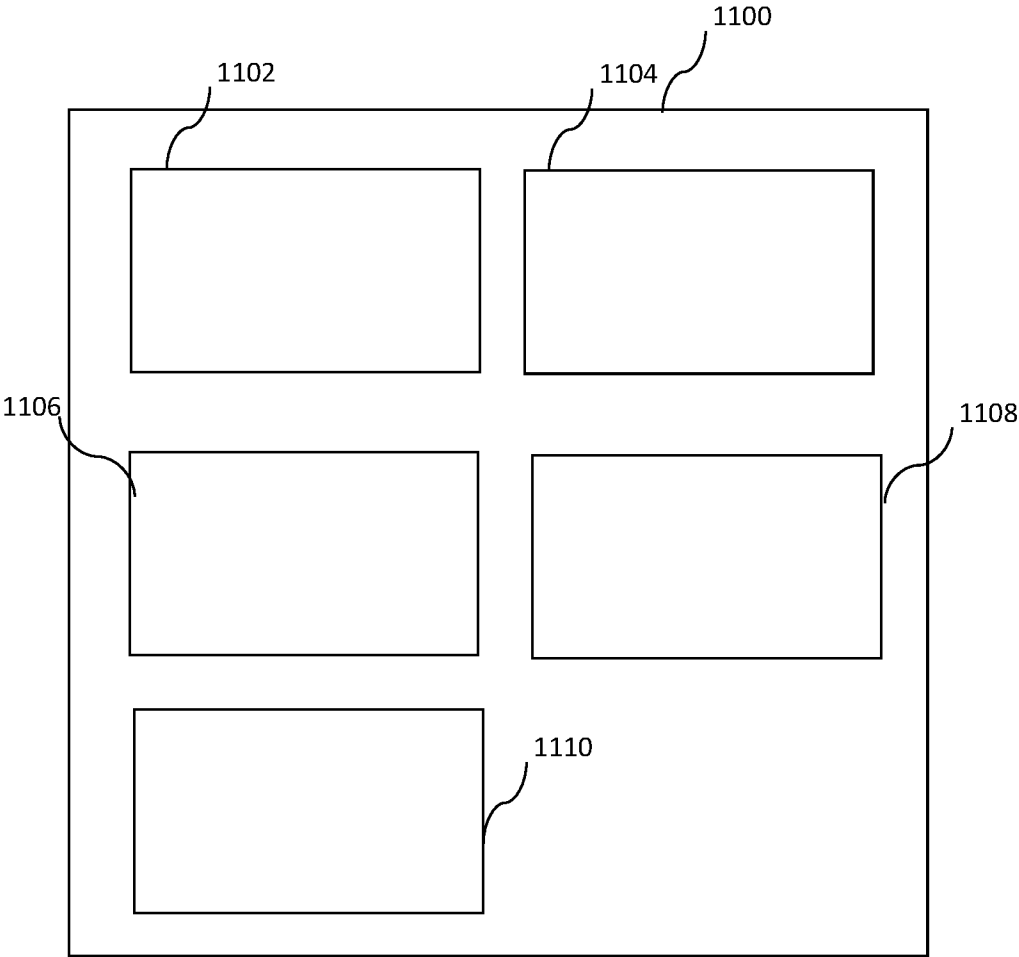


Figure 11

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2016/050138

A. CLASSIFICATION OF SUBJECT MATTER

G01N 21/62 (2006.01) G01R 27/02 (2006.01)

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01N; G01R

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)

FAMPAT, IEEE, SCOPUS: solar cell, photovoltaic, contact resistance, luminescence, photoluminescence, electroluminescence, measure, simulation, match, fit, compare and other related terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	SHANMUGAM V. ET AL., Determination of metal contact recombination parameters for silicon wafer solar cells by photoluminescence imaging. <i>SOLAR ENERGY</i> , 27 May 2015, Vol. 118, pages 20-27 [Retrieved on 2016-05-26] (DOI: 10.1016/J.SOLENER.2015.05.010) Figs. 4 and 5; 5 th page, right column	1-34
X	KILIANI D. ET AL., FITTING OF LATERAL RESISTANCES IN SILICON SOLAR CELLS TO ELECTROLUMINESCENCE IMAGES. <i>Proceedings of the 24th European PV SEC</i> , Session 2DV.1.27, Pages 2088-2090, 25 September 2009 [Retrieved on 2016-05-26] (DOI: 10.4229/24thEUPVSEC2009-2DV.1.27) Figs. 1,2 and 4; Pages 2089 and 2090	1-34
X	BREITENSTEIN O. ET AL., Photoluminescence image evaluation of solar cells based on implied voltage distribution. <i>Solar Energy Materials and Solar Cells</i> , 11 June 2014, Vol. 128, pages 296-299 [Retrieved on 2016-05-26] (DOI: 10.1016/J.SOLMAT.2014.05.040) The whole document, especially Figs. 1 and 2; Page 298	1-34

☒ 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

26/05/2015 (day/month/year)

Date of mailing of the international search report

01/06/2016 (day/month/year)

Name and mailing address of the ISA/SG

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2016/050138

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WONG J. ET AL., Differential Electroluminescence Imaging and the Current Transport Efficiency of Silicon Wafer Solar Cells. <i>2014 IEEE 40th Photovoltaic Specialist Conference (PVSC)</i> , 13 June 2014, pages 0975-0979 [Retrieved on 2016-05-26] (DOI: 10.1109/PVSC.2014.6925078) The whole document, especially Pages 0975-0976	1-34
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