# Method and Apparatus for Defect Detection

## FIELD OF THE INVENTION

**[0001]** The present invention relates to the field of solar cell manufacturing and, in particular, relates to methods and systems for utilising photoluminescence measurements to detect the influence of faults such as shunts on fully or partially processed solar cells.

## BACKGROUND

**[0002]** In silicon solar cell manufacturing, shunted cells are a common problem that reduces average production yield and average production efficiency. A 'shunt' is a local short circuit of the diode. Shunts often occur in a localised manner, caused for example by silicon nitride or silicon carbide inclusions grown-in during production of silicon ingots. These shunts can be referred to as 'material induced shunts'. Another source of shunting is non-ideal processing; for example in screen-printed silicon solar cell processing, non-ideal firing can cause shunting when the screen-printed silver is inadvertently fired through the pn-junction. These shunts can be referred to as 'processing induced shunts'.

**[0003]** In several types of industrial silicon solar cells, shunts are commonly observed around the edge of the cell. These can arise if the emitter diffusion wraps around the edge of a wafer, forming a low resistance path between the front metallisation and the rear metallisation in the finished device. Various different edge isolation techniques, including for example plasma edge isolation, laser isolation and wet chemistry single side etching, are therefore applied to every cell in production to interrupt the potential shunt path around the edge of the cell. Non-ideal processing in this edge isolation step will also cause the finished cell to have too low a shunt resistance, i.e. to be shunted. In more sophisticated cell concepts that involve the local formation of doped regions by photolithography, inkjet printing or laser doping, and where both contacts are sometimes located on the same cell surface, several other potential sources of processing induced shunting exist.

**[0004]** It has previously been demonstrated that photoluminescence (PL) measurements can be utilised to measure so-called implied current voltage characteristics of partially or fully processed solar cells over a wide range of voltages. A light source is used to illuminate the sample with variable light intensities and a detector is used to detect the PL response of the wafer from either the illuminated side or from the opposite side. The PL intensity ($I_{PL}$) can be interpreted as an implied voltage $U$ according to the equation:

$$I_{PL} = C \cdot \exp\left(\frac{eU}{kT}\right) + C_{offset} \qquad (1)$$

where $C$ is a constant that is determined largely by the sample geometry, specifically the thickness, the surface texture and the surface reflectance. In Eq. (1), $e$ represents the elementary charge, $k$ Boltzmann's constant, $T$ the sample temperature and $C_{offset}$ a correction factor that accounts for the presence of diffusion limited carriers. Sweeping the illumination intensity over a specific intensity range and measuring the PL signal simultaneously with the illumination intensity allows plotting of an implied IV curve, i.e. the illumination intensity as a function of the implied voltage that is obtained from the PL signal. This technique allows one to obtain quantitative data on electrical characteristics of partially processed cells, data which is otherwise available only after the cell production process is finished. This 'Suns-PL' technique is described in detail in T. Trupke, R.A. Bardos, M.D Abbott and J.E. Cotter, 'Suns-photoluminescence: Contactless determination of current voltage characteristics of silicon wafers', Appl. Phys. Lett. **87**, 093503 (2005), the contents of which are incorporated herein by reference. This procedure, while useful for detecting the influence of faults such as shunts, may however be too slow for in-line monitoring of a solar cell manufacturing line, where the throughput is of order one cell per second.

**[0005]** Implied current voltage measurements can also be determined, in principle, from photoconductance or other minority carrier lifetime measurements. However, in the most interesting voltage range for shunt detection (low voltages) these measurements are strongly affected by various artefacts caused by minority carrier trapping and the so-called depletion region modulation effect. These artefacts have the net result that an analysis of photoconductance measurements in terms of implied IV curves is likely to be highly inaccurate. In contrast, PL is unaffected by these artefacts, making it an ideal tool to obtain small values of implied voltages. Typical implied voltages that can be detected with PL on silicon devices are in the 250 mV to 750 mV range.

**[0006]** Suns-PL measurements on shunted cells or shunted partially processed cells are affected by the so-called diffusion limitation of the minority carrier lifetime. In the presence of shunts this leads to a contribution to the PL signal that is proportional to the incident light intensity at very small light intensities. This signal is described by the offset $C_{offset}$ in Eq. (1), and is proportional to the incident light intensity. A correction of this effect is simply achieved by subtracting the incident light intensity multiplied by a constant factor from the measured PL intensity.

**[0007]** Published PCT patent application No WO 07/041758 A1 entitled 'Method and System for Inspecting Indirect Bandgap Semiconductor Structure', the contents of which are hereby incorporated by cross-reference, discloses one form of implementation of photoluminescence measurement. In this case a multi-pixel detector, such as a CCD camera, is used to detect the

luminescence intensity distribution across the sample area. The resulting luminescence image can show the position of shunts, since the luminescence intensity in and around a shunted region is reduced in comparison to non-shunted regions. However, as discussed in O. Breitenstein, J. Bauer, T. Trupke and R.A. Bardos, 'On the Detection of Shunts in Silicon Solar Cells by Photo- and Electroluminescence Imaging', Prog. Photovolt: Res. Appl. **16**:325-330 (2008) and in M. Kasemann, D. Grote, B. Walter, W. Kwapil, T. Trupke, Y. Augarten, R.A. Bardos, E. Pink, M.D. Abbott and W. Warta, 'Luminescence Imaging for the Detection of Shunts on Silicon Solar Cells', Prog. Photovolt: Res. Appl. **16**:297-305 (2008), PL imaging is not always reliable in showing the position of shunts.

**[0008]** 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 the common general knowledge in the field.

## SUMMARY

**[0009]** It is an object of the present invention to overcome or ameliorate at least one of the disadvantages of the prior art, or to provide a useful alternative. It is an object of the present invention in its preferred form to provide a method and apparatus for reliably identifying shunted wafers at an early processing stage, with a short measurement time.

**[0010]** In accordance with a first aspect of the present invention, there is provided a method for determining an indicator of one or more electrical parameters within a solar cell or solar cell precursor, said method comprising the steps of:

(a) applying at least one low intensity illumination to said solar cell or solar cell precursor to produce photoluminescence emission from said solar cell or solar cell precursor;

(b) detecting a resulting level of said photoluminescence; and

(c) utilising the detected level of photoluminescence as an indicator of the likely electrical parameters within said solar cell, or within a solar cell produced from said solar cell precursor, wherein each said at least one low intensity illumination has an intensity of less than or equal to one Sun.

**[0011]** Preferably, at least step (a) is performed with a conductor electrically connecting different parts of a surface of the solar cell or solar cell precursor. More preferably, the different parts of the surface are electrically connected by mounting the solar cell or solar cell precursor on a metal vacuum chuck. Alternatively, the different parts of the surface are electrically connected by fully or partially immersing the solar cell or solar cell precursor in an electrically conductive liquid.

**[0012]** In one preferred form, the low intensity illumination includes a predetermined modulation and the detecting step utilises the predetermined modulation to filter noise in the detected level of photoluminescence. In another preferred form, step (a) further comprises applying a predetermined electrical modulation to the solar cell or solar cell precursor, and utilising the electrical modulation to filter noise in the detected level of photoluminescence. Preferably, the filtering of noise includes applying a lock-in signal processing technique to the detected level of photoluminescence.

**[0013]** In one preferred form, step (c) further comprises calculating from the detected level of photoluminescence the likely level of the one or more electrical parameters of the solar cell, or of a solar cell produced from the solar cell precursor. Preferably, the one or more electrical parameters include open circuit voltage. In another preferred form, step (c) further comprises dividing the detected level of photoluminescence by the background doping density of the solar cell or solar cell precursor, and the one or more electrical parameters include short circuit current. In yet another preferred form, step (c) further comprises comparing relative levels of photoluminescence measured on different samples at a same processing stage of production of the solar cell or solar cell precursor.

**[0014]** The one or more electrical parameters preferably comprise the parallel or shunt resistance of the solar cell or solar cell precursor. Preferably, the method is performed in-line on each sample or on a predetermined fraction of samples going through a solar cell production line, with a total measurement time of less than 3 seconds per sample. In preferred forms the solar cell or cell precursor is a fully processed silicon solar cell or a partially processed silicon wafer. Preferably, the low intensity illumination light has an incident photon flux of less than about $<10^{17}cm^{-2}s^{-1}$.

**[0015]** Preferably, the method is utilised in a solar cell production line after an emitter formation step. In one preferred form, the method is performed without removal of any phosphorus glass layer produced in the emitter formation step. Alternatively, the method is performed after removal of any phosphorus glass layer produced in the emitter formation step from at least a rear surface of the solar cell or solar cell precursor, the rear surface being opposite the surface on which the emitter is formed. Preferably, the method is performed after removal of a native oxide layer from at least a rear surface of the solar cell or solar cell precursor, the rear surface being opposite the surface on which the emitter is formed.

**[0016]** In preferred forms, the method is utilised in a solar cell production line after an edge isolation step. Preferably, the edge isolation step comprises plasma edge isolation, laser edge isolation, or floating edge isolation. Alternatively, the method is utilised in a solar cell production line during a floating edge isolation step, wherein the etching liquid utilised in the floating edge isolation step is electrically conductive.

**[0017]** The method is preferably utilised in a spatially resolved manner across a surface of the solar cell or solar cell precursor.

**[0018]** Preferably, the low intensity illumination comprises an illumination pulse of less than 3 seconds duration.

**[0019]** In preferred forms, step (c) further comprises constructing an implied I-V curve of the solar cell or solar cell precursor. Preferably, multiple different low intensity illuminations are utilised in an iterative manner to build up a corresponding implied I-V curve of the solar cell or solar cell precursor.

**[0020]** Preferably, the method further comprises the step of: (d) utilising the indicator of the likely electrical parameters for quality control, process control or process monitoring in the production of solar cells or of silicon wafers. The method is preferably performed in-line in a solar cell production line, and the detected level of photoluminescence is used to sort the solar cells or solar cell precursors into quality bins.

**[0021]** In accordance with a second aspect of the present invention, there is provided a method for measuring properties of a solar cell material, said method comprising the steps of:

(a) illuminating said solar cell material with an illumination having an intensity of less than or equal to one Sun, to generate photoluminescence from said solar cell material;

(b) modulating the level of said illumination or electrically modulating said solar cell material with a predetermined modulation to produce a resultant modulation in said photoluminescence;

(c) detecting said photoluminescence; and

(d) filtering the detected photoluminescence based upon said predetermined modulation.

**[0022]** Preferably, the predetermined modulation comprises modulation at a predetermined frequency and the filtering step utilises lock-in techniques on the predetermined frequency to filter noise associated with the detected photoluminescence.

**[0023]** In accordance with a third aspect of the present invention, there is provided a method for monitoring an edge isolation process in a solar cell production line, said method comprising the steps of: (a) applying an illumination to a solar cell precursor before said edge isolation process; (b) detecting photoluminescence emitted from said solar cell precursor as a result of said illumination, to obtain a first photoluminescence level; (c) repeating steps (a) and (b) after said edge isolation process, to obtain a second photoluminescence level; and (d) comparing said first and second photoluminescence levels to obtain a measure of the effectiveness of said edge isolation process. Preferably, the illumination has an intensity of less than or equal to one Sun.

**[0024]** In accordance with a fourth aspect of the present invention, there is provided a method for monitoring an edge isolation process in a solar cell production line, said method comprising the steps of: (a) applying an illumination to a solar cell or solar cell precursor after said edge isolation process; (b) obtaining an image of the photoluminescence emitted from said solar cell or solar cell precursor as a result of said illumination; and (c) analysing the relative intensity of photoluminescence emitted from peripheral portions of said solar cell or solar cell precursor to obtain a measure of the effectiveness of said edge isolation process.

**[0025]** Preferably, the method further comprises the step of: (d) comparing the image with a corresponding photoluminescence image obtained before the edge isolation step. Preferably, the illumination has an intensity of less than or equal to one Sun.

**[0026]** In accordance with a fifth aspect of the present invention, there is provided a method for monitoring the progress of an edge isolation process in a solar cell production line, said method comprising the steps of: (a) applying an illumination to a solar cell precursor at a first time in said edge isolation process; (b) detecting photoluminescence emitted from said solar cell precursor as a result of said illumination, to obtain a first photoluminescence level; (c) repeating steps (a) and (b) for said solar cell precursor at a second, later time in said edge isolation process, to obtain a second photoluminescence level; and (d) comparing said first and second photoluminescence levels.

**[0027]** In one preferred form, step (a) is performed before the commencement of the edge isolation process. Preferably, the illumination has an intensity of less than or equal to one Sun.

**[0028]** In accordance with a sixth aspect of the present invention, there is provided a system when implementing a method in accordance with any of the first, second, third, fourth or fifth aspects of the present invention.

**[0029]** For the purposes of this specification, the terminology 'in-line measurement' can have the meaning that either every wafer going through a solar cell production line is measured, or that samples are taken from the production line at predetermined intervals (for example every $20^{th}$ wafer) for measurement.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0030]** Benefits and advantages of the present invention will become apparent to those skilled in the art to which this invention relates from the subsequent description of exemplary embodiments and the appended claims, taken in conjunction with the accompanying drawings, in which:

Fig. 1 illustrates implied IV curves for different levels of diode shunt;

Fig. 2 illustrates schematically some common origins of shunting in a solar cell;

Fig. 3 shows a PL image of an emitter-diffused silicon wafer, with bright areas around the edge indicative of potential process-induced shunting; and

Fig. 4, Fig. 5 and Fig. 6 illustrate schematically different operational setups of the preferred embodiments.

## DETAILED DESCRIPTION OF THE PREFERRED AND OTHER EMBODIMENTS

**[0031]** Implied IV curves, measured on solar cells by the Suns-PL technique for example, can reveal the presence of shunts. Fig. 1 shows a graph with three simulated implied IV curves, one (curve 1) for an ideal cell with infinite shunt resistance (i.e. no influence of shunts on the cell performance) and two (curves 2, 3) calculated for two different finite shunt resistance values where the shunt resistance of curve 2 is less than curve 3. The graph shows that a low shunt resistance reduces the diode voltage particularly at low illumination intensities (equivalent to low luminescence signals and thus low voltages) whereas the IV curves at large voltages are only marginally affected by the shunt value. In other words, the effect of shunts on solar cells is most noticeable at low light levels. The entire implied current voltage characteristics at low illumination as shown in Fig. 1 can be utilised to obtain quantitative information about the shunt resistance even before the cell is metallised. Suns-PL is therefore one PL-based metrology method that can reveal potential shunts in solar cells at an early stage in their manufacture.

**[0032]** Inclusions are a common form of material induced shunting in solar cells. In multicrystalline silicon wafers for example, typical inclusions include silicon carbide and silicon nitride. These are normally found to be n-type and occur in the form of long and narrow needles. As shown schematically in Fig. 2, an inclusion **20** can connect the front surface **21** and rear surface **22** of a silicon wafer **23** being processed into a solar cell. Fig. 2 also shows a common cause of 'process induced shunting' in solar cells, a side effect of emitter diffusion. For a silicon solar cell with a p-type base, the emitter will be n-doped, typically with phosphorus, while the emitter will be p-doped, typically with boron, for an n-type base. Ideally the emitter layer **24** should only be present on the front surface of the wafer. However in typical emitter formation processes such as thermal diffusion, the diffused region wraps around to form doped regions at the wafer sides **25** and at the peripheral portions **26** of the rear surface. This 'wrap around' emitter layer can form a low resistance path between the front and rear metallisations of a finished device.

**[0033]** Fig. 3 shows a PL image **31** taken on an emitter-diffused silicon wafer, with illumination and PL detection from the rear surface of the wafer. The bright areas **32** around the edges of the image reveal regions that have inadvertently been emitter diffused on both sides. The higher

luminescence intensity from these areas is a result of the field effect passivation on both sides, whereas in the central region the illuminated rear surface is unpassivated, resulting in a low count rate. PL imaging is therefore another PL-based metrology method that can reveal potential shunts in solar cells at an early stage in their manufacture.

**[0034]** It is important to realise however that both sources of shunting illustrated in Fig. 2, i.e. inclusions and inadvertent emitter wrap-around, become fully activated only when the interface between the p-type base and the n-doped emitter (or vice versa in n-type cells), or between the base and an inclusion, is connected with a metal **27** or some other conductor. In finished screen-printed solar cells for example, this occurs when the aluminium rear contact across the entire rear surface is deposited and then fired. All pn-junctions or inclusions located under the metal are shorted in that process, but until that time they are only potential shunts. This has important implications for early stage monitoring of shunting problems during solar cell manufacture. For reliable early stage monitoring, the potential shunts must be short circuited, or at least connected with a low resistance path, to become detectable. Preferably, the PL-based metrology methods of the present invention are performed with a conductor connecting different parts of the rear surface of the sample electrically. In one embodiment the potential shunts are activated by sucking or pressing the sample onto a metal chuck, e.g. a vacuum chuck. In alternative embodiments the sample can be immersed in or floating on the surface of a conductive liquid, or sucked or pressed onto a conductive sample holder with a thin layer of conductive liquid between the two.

**[0035]** Another complication for early stage shunt detection is that thermal diffusion of an emitter tends to leave a thin highly doped oxide layer at the surface. For a phosphorus-doped emitter layer for example, this oxide layer is the so-called 'phosphorus glass'. This oxide layer may be electrically insulating, which means that the abovementioned methods for establishing contact between the sample and a solid or liquid conductor may not always establish electrical contact (and therefore activate the potential shunts) immediately after the emitter diffusion process. In certain embodiments, the PL-based metrology methods of the present invention are performed after removal of the phosphorus glass or similar oxide layer from at least the rear surface of the sample. An additional complication can arise from the fact that a native oxide layer forms on the surface of silicon wafers after some time, typically within a few minutes after a bare surface has been formed, e.g. by etching. This native oxide may also have to be removed, at least from the rear surface, to detect potential shunts reliably.

**[0036]** Because of the propensity for a diffused emitter layer to wrap around the wafer edge, an edge isolation technique is routinely applied to every cell in production to interrupt the potential shunt path. In one such technique, known as laser edge isolation, a laser is used to cut a thin trench into the emitter. In current production lines this process is performed on finished cells, but it could

in principle be performed immediately after phosphorus glass removal. Another edge isolation technique is plasma edge isolation, where a plasma etching process removes the emitter layer from the edge of the wafer. This process is usually performed with a large number of wafers stacked on top of each other. In yet another edge isolation technique, based on wet chemical etching, wafers are floated or supported on the surface of an etching bath such that only the rear surface and part of the edge are immersed in the etching solution and become etched. We will refer to this technique as 'floating edge isolation'.

**[0037]** It follows then that the PL-based metrology methods of the present invention can be used to monitor edge isolation techniques, in that if the potential shunt disappears, then the edge isolation has been effective. On the other hand, and with reference to the PL image shown in Fig. 3, if bright peripheral regions **32** are present after edge isolation, then it is likely the edge isolation has not been completely effective. In certain embodiments, the PL-based metrology is performed after a plasma edge isolation step, or after a laser edge isolation step, or after a floating edge isolation step. Optionally, the 'after' results can be compared with corresponding results obtained before edge isolation. PL-based metrology can also be used to monitor the progress of a floating edge isolation step if the etching solution is sufficiently conductive, since the etching solution is in contact with the entire rear surface of the wafer. Alternatively, PL-based metrology can be used to monitor the progress of a laser edge isolation step if the wafer is sucked or pressed onto a conductive holder for example.

**[0038]** In yet another PL-based metrology method, a single luminescence measurement at one specific illumination intensity may be used to obtain a single value for the implied voltage via Eq. (1). That implied voltage may then be used as a figure of merit or as a decision criterion in production for further action.

**[0039]** The conversion of the luminescence intensity to implied voltage according to Eq. (1) requires knowledge of the constant $C$ and of the offset value $C_{offset}$. For in-line applications however, where measurement speed is of the essence, the luminescence signal itself (measured with a given experimental set up) may be used as the decision criterion. For example a specific luminescence intensity value may be used as a threshold criterion to sort wafers or cells into different quality bins. That is, knowledge of the absolute value of the implied voltage is not essential for assessing the likely effects on cell performance of faults such as shunts or potential shunts.

**[0040]** In certain embodiments, the luminescence measurement can be performed with illumination and detection from the same side of the wafer, while in other embodiments it can be performed with illumination and detection from opposite sides of the wafer. In various

embodiments the luminescence can be measured in a spatially resolved fashion (e.g. luminescence imaging using a CCD camera) or in a non-spatially resolved fashion (e.g. using a large area photodiode in combination with a preamplifier) or via mapping. In certain embodiments the illumination can be homogeneous over the entire wafer area. In alternative embodiments only part of the wafer is illuminated, as explained in Australian provisional patent application No 2009902178 entitled 'Material or device characterisation with non-homogeneous excitation' and incorporated herein by reference, this would still excite the entire wafer, at least at low illumination intensities, if an emitter is present.

**[0041]** The luminescence measurement can take place very quickly with example measurement times of less then two seconds, so that every wafer going through a solar cell production can be monitored. That monitoring may even take place while the wafers are in motion on a conveyor belt. In this case the optics and detection system can be moved in parallel with the samples. Alternatively the illumination and detection system may be static, in which case a line scan along each wafer would be measured or a static image constructed from a 2-D photodetector. Alternatively the samples may be held stationary during measurement, which would suit an area imaging measurement.

**[0042]** Shunted and non-shunted wafers can then be binned according to a threshold implied voltage or luminescence signal. For example wafers with an implied voltage below that threshold voltage, or with a luminescence signal below that threshold signal, can be classified as shunted. A single luminescence measurement would normally be performed at a low illumination intensity, preferably with incident photon flux $<3x10^{17}cm^{-2}s^{-1}$ (approximately 1 Sun), more preferably $<10^{17}cm^{-2}s^{-1}$, since the impact of shunts on the diode voltage, and therefore on the luminescence signal, is more pronounced at low illumination as illustrated in Fig. 1. For the purposes of this specification, an incident photon flux of $3x10^{17}cm^{-2}s^{-1}$ is considered to be 1 Sun.

**[0043]** It should be noted that although shunting is a likely cause of a wafer being 'below threshold', especially at low illumination, there could be other causes, for example a large region of low lifetime material. Consequently, while the PL-based metrology methods of the present invention are designed primarily to detect the influence of shunts on solar cells and solar cell precursors, they are not so limited.

**[0044]** PL-based shunt detection can in principle be performed in two fundamentally different ways, being either spatially resolved or non-spatially resolved. In both cases an illumination source is used to illuminate the entire wafer or part of the wafer and a photoluminescence (PL) detector is used to capture the emitted luminescence light. The detector can be located on either side of the wafer with respect to the illumination source. In a first example case illustrated in Fig. 4, the

illumination source 40 and detector 41 are on the same side of the sample 42. In a second example illustrated in Fig. 5, the illumination source 40 is provided on a first side of the sample 42 and the detector 41 mounted directly behind the sample, in which case the detector picks up a large fraction of the PL emission from the area 50 that it is mounted under. Alternatively, as illustrated in Fig. 6, the detector 41 is mounted at some distance from the sample 42, resulting in the collection of a smaller fraction of the luminescence signal but from a larger sample area.

**[0045]** With regard to the arrangement of Fig. 5, the luminescence detector 41 may be substantially smaller in size (e.g. 2x2 $cm^2$) than the sample 42 (typically >10x10 $cm^2$). Therefore it is advantageous to perform the luminescence measurement with a low illumination intensity since the influence of shunts located in the wafer outside the area 50 that is on top of the detector will still cause the luminescence intensity to be reduced across the entire wafer area, since the emitter effectively electrically connects the different parts of the cell (shunted and non-shunted) in parallel. The PL intensity from the non-shunted areas can thus be dragged down by the shunted areas. Towards higher illumination intensities however the limited conductance of the emitter increasingly isolates shunted and non-shunted regions laterally. Since the emitter is normally designed for about one-Sun equivalent illumination intensity, a single PL measurement (spatially resolved or non-spatially resolved) is preferably performed at an illumination intensity smaller than one-Sun equivalent, i.e. with an incident photon flux less than $3x10^{17}$ $cm^{-2}s^{-1}$.

**[0046]** Dedicated optical filters can be used to avoid excitation light contributing to the measured PL signal. Generally this is achieved by long pass filtering the detected luminescence signal using a long pass filter in front of the sensor, that transmits a large fraction of the luminescence signal but blocks the excitation light. A short pass filter with a shorter cut-off wavelength than the cut-off of the long pass filter is used to filter the excitation light to block any long wavelength components in the excitation spectrum that, after reflection off the sample surface (or via transmission through the wafer) could be detected by the sensor. Because the luminescence intensity from an indirect bandgap material such as silicon is typically several orders of magnitude weaker than the excitation light, and reflection of the excitation light from a silicon wafer can be on the orders of several percent to tens of percent, the filtering needs to be highly efficient. In the geometries shown in Fig. 5 and Fig. 6, the silicon wafer can itself act as an efficient long pass filter. For example if an excitation wavelength of 800 nm is used, the fraction of transmitted excitation light would be $<10^{-6}$ for a 200 μm thick silicon wafer. No further long pass filtering may be required in that case, however efficient short pass filtering of the excitation light would still be required.

**[0047]** Several light sources can potentially be used for excitation, including lasers, light emitting diodes, halogen lamps and flash lamps.

**[0048] Non-spatially resolved measurements:** In certain embodiments a single photo-detector is used to capture a spatially averaged photoluminescence signal. Examples of typical photodiodes that could be used to detect PL emission from silicon samples are detectors made from crystalline silicon (Si), indium-gallium-arsenide (InGaAs), germanium (Ge) or SiGe alloys in combination with low noise preamplifiers. Other sample materials will generally emit PL in different wavelength ranges, and suitable detectors will be known to those skilled in the art. In embodiments with time-resolved measurements, detectors can be used to capture the time dependent luminescence intensity during and after an illumination light pulse. Typically, illumination pulses will be one millisecond to a few seconds in duration. In alternative embodiments, detectors can be used to measure a constant PL signal generated by illumination of the wafer with constant intensity. In other embodiments the illumination is modulated periodically with a known frequency, to perform the PL intensity measurement via a lock-in technique. That way the influence of ambient light in a production environment can be greatly reduced.

**[0049] Spatially resolved measurements:** PL imaging is an attractive measurement technique for fast spatially resolved measurement of the luminescence intensity. In this case, a luminescence intensity value is measured for each spatially resolved part of the cell in a single luminescence image. In principle then, a local implied diode voltage can be calculated for each pixel of a luminescence image. An illumination intensity dependence and thus an implied IV curve can then be calculated for each detector pixel if several PL imaging measurements are performed with different illumination intensities. Since the impact of shunts is most significant at low implied voltages, i.e. at low illumination intensities where the PL signal is low, longer integration times may be required. To avoid longer integration time, and therefore longer measurement time, the spatial resolution of the camera may be reduced by pixel binning. For example combining 5x5 pixels into a single pixel will increase the count rate by a factor of 25, but reduce the spatial resolution. Alternatively, one can use higher sensitivity cameras.

**[0050]** The above described PL-based metrology methods are most usefully applied at or after any processing stage after an emitter has been diffused or otherwise processed into one or both surfaces of the sample, to form a pn-junction. Referring to Figs 4, 5 and 6, the illuminated surface of the sample **42** need not correspond to an emitter-diffused surface, but may be chosen for measurement convenience. In cell designs such as screen-printed cells, a non-spatially resolved measurement does not distinguish between edge shunts, which appear in almost every cell (at least before edge isolation), and other shunts caused by inclusions for example. A suitable application for non-spatially resolved shunt detection is therefore after edge isolation, in which case PL-based qualitative or quantitative shunt analysis can give information about non-optimal edge isolation or about other shunts in the sample.

**[0051]** The as-measured PL data can be used to get either quantitative information about the shunt strength, or qualitative information about the shunt strength relative to a threshold value. In qualitative embodiments there is no conversion of the measured PL signal into an implied voltage or any other physical parameter, rather the spatially resolved or spatially averaged luminescence signal itself would be used as a figure of merit. Wafers that emit a PL signal above or below specific threshold values would be binned into separate quality bins. In preferred embodiments the measurements are fast enough to be performed in-line on every wafer going through a production facility, or on a significant percentage of the wafer throughput.

**[0052]** Information about shunts in a wafer derived from PL-based metrology methods of the present invention may subsequently result in a number of possible actions. For example the wafer may be removed from the processing line for reprocessing or return to the wafer supplier, or for sorting of samples for later processing steps. In other examples, corrective action can be taken on a process step or tool if the shunt is caused by a process engineering fault, or corrective action can be taken by a material supplier if the shunt is caused by a material fault. In yet other examples the wafer can be reprocessed for shunt remediation, or 'tagged' for an in-line process variation to reduce the impact of the shunt.

**[0053]** The measured PL signal at an intermediate processing step may also be used as a metric that allows correlation with final cell open circuit voltage, $V_{oc}$. In solar cell production this may be used by establishing statistical relationships between the PL signal at specific processing steps and final cell data. That information may be used to identify quickly the origin of reduced final cell performance, for example by identifying the exact processing step after which significant deviations from the expected statistical relationship occur. Such statistical relationships may also be used as a more efficient way to tune the processing parameters of individual processing steps. The PL signal measured with low illumination intensity may also be used as input parameter in a Manufacturing Execution System (MES).

**[0054]** As discussed above, the luminescence intensity can be interpreted as a measure of the cell voltage, with the two related by Eq. (1). On the other hand the luminescence intensity divided by the background doping density of the base material, referred to as the doping-normalised PL signal, is correlated with the excess minority carrier lifetime and therefore the cell short circuit current, $I_{sc}$. Similar correlations and analysis applications as described in the previous paragraph can thus be established between a spatially resolved or spatially averaged doping-normalised PL signal and the short circuit current, or the current extracted at the maximum power point. An area average of the luminescence intensity from an entire partially processed wafer is preferable in this case over the signal from only part of the wafer.

**[0055]** A single non-spatially resolved PL measurement can proceed as follows. Step 1: Illumination of the wafer or part of the wafer with a given illumination intensity, preferably less or equal to than 1 Sun, more preferably less than $10^{17}\,cm^{-2}s^{-1}$. The illumination may be constant for steady-state measurements or pulsed for time-resolved measurements. Alternatively the illumination intensity may be modulated and the PL measurement performed via a lock-in technique. In this case the signal may be fully modulated or consist of a modulated contribution plus a constant offset. Step 2: Measurement of the resulting area-averaged luminescence intensity (using one of the above-described area-detection geometries). Step 3: Comparison of the measured luminescence intensity with a threshold luminescence intensity and binning into shunted or non-shunted bins or into finer shunt-classes.

**[0056]** Multiple non-spatially resolved PL measurements can proceed by the following steps. Step 1: Illumination of the wafer with a pulse typically 1 ms to 5 s duration, or with a sequence of several discrete illumination intensities. Step 2: Measurement of both the time dependent illumination intensity and of the time dependent luminescence intensity. Step 3: Calculation of the implied IV curve as described previously. This requires knowledge of a calibration factor ($C$ in Eq. (1)), which will be similar for multiple samples of the same type. Consequently this calibration factor only needs to be determined once, as using the same calibration factor for different samples of the same type will only marginally affect the accuracy. Alternatively the PL signal itself may be used as a figure of merit. Step 4: Construction of the Suns-PL curve and analysis of this curve to get quantitative shunt resistance data.

**[0057]** A single spatially resolved PL image measurement can proceed by the following steps. Step 1: PL image the wafer with one specific illumination intensity, preferably at or below 1 Sun, more preferably below $10^{17}\,cm^{-2}s^{-1}$. Step 2: Conduct an analysis of the average luminescence intensity. Step 3: Compare the measured average luminescence intensity with a threshold average luminescence intensity and bin the samples into shunted or non-shunted bins.

**[0058]** Multiple spatially resolved PL image measurements can proceed by the following steps. Step 1: Measure several PL images with different steady state illumination intensities with each intensity preferably at or below 1 Sun, more preferably below $10^{17}\,cm^{-2}s^{-1}$. Step 2: Plot the illumination intensity as a function of the implied voltage for individual pixels. Step 3: Determine an implied IV curve for each pixel. Step 4: From the implied IV curve, perform a statistical data analysis based on the spatially resolved implied IV curves and subsequently bin the wafers based on IV curve outcomes.

**[0059]** In summary, the PL-based metrology methods of the preferred embodiments provide a technique for determining the presence or influence of faults, particularly shunts or potential shunts,

in a fully or partially processed solar cell, that will reduce the performance of finished solar cells. The methods are applicable to wafers or thin films at any solar cell processing stage after emitter diffusion. The methods can be used in a spatially resolved or non-spatially resolved detection manner, and are suitable for a single intensity or up to a complete Suns-PL curve. The methods can provide a quantitative analysis of the resistance value of shunts or potential shunts, or a qualitative analysis based on thresholding. The methods can be used in production for quality control, process control and process monitoring. Preferably, the methods are used with PL generated from illumination intensities less than or equal to one Sun.

**[0060]** In certain embodiments, the processing train utilises 'lock-in' signal processing to provide a highly noise immune processing environment. Without lock-in processing, the noise floor at the detector may be the sum of ambient light (which may be minimal if the detection takes place in a light-tight box for laser safety reasons) and, more importantly, reflected excitation light and any PL resulting from the emission of the sample stage and its surrounds. This often requires the use of a combination of exacting optical filters to filter out reflected excitation light and ambient light from the PL signal at the camera. If the camera is silicon-based, it acts as a short pass filter itself. The combination of filters and choice of camera is directed at making an extremely selective band pass filter of interest.

**[0061]** In embodiments using lock-in processing, the requirements are less exacting. The methods can be implemented with other light sources, e.g. visible light sources and non-laser sources, and less specialised camera devices. The optical filters may also not be required, and if visible light or non-laser sources are utilised, laser safety equipment may not be required. Further, it is possible to use processing materials in and around the sample stage that have a significant PL emission. One key element in opening up the design constraints in these alternative embodiments is the utilisation of a lock-in signal processing approach. Examples of lock-in signal processing are well known and a general reference can be found at: http://en.wikipedia.org/wiki/Lock-in_amplifier.

**[0062]** Lock-in techniques can be used in at least two ways. In one example embodiment the lock-in signal is superimposed on the excitation light by modulating the light source intensity. In another example embodiment the lock-in signal is superimposed as a perturbation to the PL emission from the sample, for example by applying an electrical potential or current to a wafer or cell via backside or topside electrical contacts or both. The applied potential or current need not be sufficient to create electroluminescence (EL), but need only create an observable variation in the measured PL signal that is a signature of the lock-in carrier signal. The latter of these two approaches may be preferable since it enables the PL emission to be de-convoluted from noise from both ambient light and reflected light (including any PL emission in the sample area that comes from materials in the sample stage).

**[0063]** Another advantage of using lock-in processing is the ability to use a fast camera detector that can integrate the signal many times in a second, thereby speeding up measurement times substantially to enhance the use of the PL-based metrology methods in fast in-line manufacturing applications.

*Interpretation*

**[0064]** Unless the context clearly requires otherwise, throughout the description and the claims, the words 'comprise', 'comprising', and the like are to be construed in an inclusive sense as opposed to an exclusive or exhaustive sense; that is to say, in the sense of 'including, but not limited to'.

**[0065]** Reference throughout this specification to 'one embodiment' or 'an embodiment' means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, appearances of the phrases 'in one embodiment' or 'in an embodiment' in various places throughout this specification are not necessarily all referring to the same embodiment, but may. Furthermore, the particular features, structures or characteristics may be combined in any suitable manner, as would be apparent to one of ordinary skill in the art from this disclosure, in one or more embodiments.

**[0066]** Similarly it should be appreciated that in the above description of exemplary embodiments of the invention, various features of the invention are sometimes grouped together in a single embodiment, figure, or description thereof for the purpose of streamlining the disclosure and aiding in the understanding of one or more of the various inventive aspects. This method of disclosure, however, is not to be interpreted as reflecting an intention that the claimed invention requires more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects lie in less than all features of a single foregoing disclosed embodiment. Thus, the claims following the Detailed Description are hereby expressly incorporated into this Detailed Description, with each claim standing on its own as a separate embodiment of this invention.

**[0067]** Furthermore, while some embodiments described herein include some but not other features included in other embodiments, combinations of features of different embodiments are meant to be within the scope of the invention, and form different embodiments, as would be understood by those in the art. For example, in the following claims, any of the claimed embodiments can be used in any combination.

**[0068]** Furthermore, some of the embodiments are described herein as a method or combination of elements of a method that can be implemented by a processor of a computer system or by other means of carrying out the function. Thus, a processor with the necessary instructions for carrying

out such a method or element of a method forms a means for carrying out the method or element of a method. Furthermore, an element described herein of an apparatus embodiment is an example of a means for carrying out the function performed by the element for the purpose of carrying out the invention.

**[0069]** In the description provided herein, numerous specific details are set forth. However, it is understood that embodiments of the invention may be practiced without these specific details. In other instances, well-known methods, structures and techniques have not been shown in detail in order not to obscure an understanding of this description.

**[0070]** As used herein, unless otherwise specified the use of the ordinal adjectives 'first', 'second', 'third', etc, to describe a common object, merely indicate that different instances of like objects are being referred to, and are not intended to imply that the objects so described must be in a given sequence, either temporally, spatially, in ranking, or in any other manner.

**[0071]** In the claims below and the description herein, any one of the terms comprising, comprised of or which comprises is an open term that means including at least the elements/features that follow, but not excluding others. Thus, the term comprising, when used in the claims, should not be interpreted as being limitative to the means or elements or steps listed thereafter. For example, the scope of the expression a device comprising A and B should not be limited to devices consisting only of elements A and B. Any one of the terms including or which includes or that includes as used herein is also an open term that also means including at least the elements/features that follow the term, but not excluding others. Thus, including is synonymous with and means comprising.

**[0072]** Similarly, it is to be noticed that the term 'coupled', when used in the claims, should not be interpreted as being limitative to direct connections only. The terms 'coupled' and 'connected', along with their derivatives, may be used. It should be understood that these terms are not intended as synonyms for each other. Thus, the scope of the expression a device A coupled to a device B should not be limited to devices or systems wherein an output of device A is directly connected to an input of device B. It means that there exists a path between an output of A and an input of B which may be a path including other devices or means. 'Coupled' may mean that two or more elements are either in direct physical or electrical contact, or that two or more elements are not in direct contact with each other but yet still co-operate or interact with each other.

**[0073]** Although the present invention has been described with particular reference to certain preferred embodiments thereof, variations and modifications of the present invention can be effected within the spirit and scope of the following claims.

We claim:

1. A method for determining an indicator of one or more electrical parameters within a solar cell or solar cell precursor, said method comprising the steps of:

(a) applying at least one low intensity illumination to said solar cell or solar cell precursor to produce photoluminescence emission from said solar cell or solar cell precursor;

(b) detecting a resulting level of said photoluminescence; and

(c) utilising the detected level of photoluminescence as an indicator of the likely electrical parameters within said solar cell, or within a solar cell produced from said solar cell precursor, wherein each said at least one low intensity illumination has an intensity of less than or equal to one Sun.

2. A method as claimed in claim 1, wherein at least step (a) is performed with a conductor electrically connecting different parts of a surface of said solar cell or solar cell precursor.

3. A method as claimed in claim 2, wherein said different parts of said surface are electrically connected by mounting said solar cell or solar cell precursor on a metal vacuum chuck.

4. A method as claimed in claim 2, wherein said different parts of said surface are electrically connected by fully or partially immersing said solar cell or solar cell precursor in an electrically conductive liquid.

5. A method as claimed any one of the preceding claims, wherein said low intensity illumination includes a predetermined modulation and said detecting step utilises said predetermined modulation to filter noise in said detected level of photoluminescence.

6. A method as claimed in any one of claims 1 to 4, wherein said step (a) further comprises applying a predetermined electrical modulation to said solar cell or solar cell precursor, and utilising said electrical modulation to filter noise in said detected level of photoluminescence.

7. A method as claimed in claim 5 or claim 6, wherein said filtering of noise includes applying a lock-in signal processing technique to said detected level of photoluminescence.

8. A method as claimed in any one of the preceding claims, wherein said step (c) further comprises calculating from said detected level of photoluminescence the likely level of said one or more electrical parameters of the solar cell, or of a solar cell produced from said solar cell precursor.

9. A method as claimed in claim 8, wherein said one or more electrical parameters comprise open circuit voltage.

10. A method as claimed in claim 8, wherein step (c) further comprises dividing said detected level of photoluminescence by the background doping density of said solar cell or solar cell precursor, and said one or more electrical parameters comprise short circuit current.

11. A method as claimed in any one of claims 1 to 7, wherein said step (c) further comprises comparing relative levels of photoluminescence measured on different samples at a same processing stage of production of said solar cell or solar cell precursor.

12. A method as claimed in any one of the preceding claims, wherein said one or more electrical parameters comprise the parallel or shunt resistance of said solar cell or solar cell precursor.

13. A method as claimed in any one of the preceding claims, wherein said method is performed in-line on each sample or on a predetermined fraction of samples going through a solar cell production line, with a total measurement time of less than 3 seconds per sample.

14. A method as claimed in any one of the preceding claims, wherein said solar cell or cell precursor is a fully processed silicon solar cell or a partially processed silicon wafer.

15. A method as claimed in any one of the preceding claims, wherein said low intensity illumination has an incident photon flux of less than about $10^{17}cm^{-2}s^{-1}$.

16. A method as claimed in any one of the preceding claims, wherein said method is utilised in a solar cell production line after an emitter formation step.

17. A method as claimed in claim 16, wherein said method is performed without removal of any phosphorus glass layer produced in said emitter formation step.

18. A method as claimed in claim 16, wherein said method is performed after removal of any phosphorus glass layer produced in said emitter formation step from at least a rear surface of said solar cell or solar cell precursor, said rear surface being opposite the surface on which the emitter is formed.

19. A method as claimed in any one of claims 16 to 18, wherein said method is performed after removal of a native oxide layer from at least a rear surface of said solar cell or solar cell precursor, said rear surface being opposite the surface on which the emitter is formed.

20. A method as claimed in any one of claims 16 to 19, wherein said method is utilised in a solar cell production line after an edge isolation step.

21. A method as claimed in claim 20, wherein said edge isolation step comprises plasma edge isolation, laser edge isolation, or floating edge isolation.

22. A method according to any one of claims 16 to 19, wherein said method is utilised in a solar cell production line during a floating edge isolation step, wherein the etching liquid utilised in said floating edge isolation step is electrically conductive.

23. A method as claimed in any one of the preceding claims, wherein said method is utilised in a spatially resolved manner across a surface of said solar cell or solar cell precursor.

24. A method as claimed in any one of the preceding claims, wherein said low intensity illumination comprises an illumination pulse of less than 3 seconds duration.

25. A method as claimed in any one of the preceding claims, wherein said step (c) further comprises constructing an implied I-V curve of said solar cell or solar cell precursor.

26. A method as claimed in claim 1, wherein multiple different low intensity illuminations are utilised in an iterative manner to build up a corresponding implied I-V curve of said solar cell or solar cell precursor.

27. A method according to any one of the preceding claims, wherein said method further comprises the step of: (d) utilising said indicator of the likely electrical parameters for quality control, process control or process monitoring in the production of solar cells or of silicon wafers.

28. A method according to any one of the preceding claims, wherein said method is performed in-line in a solar cell production line, and said detected level of photoluminescence is used to sort said solar cells or solar cell precursors into quality bins.

29. A system when implementing the method of any one of claims 1 to 28.

30. A method for measuring properties of a solar cell material, said method comprising the steps of:

(a) illuminating said solar cell material with an illumination having an intensity of less than or equal to one Sun, to generate photoluminescence from said solar cell material;

(b) modulating the level of said illumination or electrically modulating said solar cell material with a predetermined modulation to produce a resultant modulation in said photoluminescence;

(c) detecting said photoluminescence; and

(d) filtering the detected photoluminescence based upon said predetermined modulation.

31. A method as claimed in claim 30, wherein said predetermined modulation comprises modulation at a predetermined frequency and said filtering step utilises lock-in techniques on said predetermined frequency to filter noise associated with the detected photoluminescence.

32. A system when implementing the method of claim 30 or claim 31.

33. A method for monitoring an edge isolation process in a solar cell production line, said method comprising the steps of: (a) applying an illumination to a solar cell precursor before said edge isolation process; (b) detecting photoluminescence emitted from said solar cell precursor as a result of said illumination, to obtain a first photoluminescence level; (c) repeating steps (a) and (b) after said edge isolation process, to obtain a second photoluminescence level; and (d) comparing said first and second photoluminescence levels to obtain a measure of the effectiveness of said edge isolation process.

34. A method for monitoring an edge isolation process in a solar cell production line, said method comprising the steps of: (a) applying an illumination to a solar cell or solar cell precursor after said edge isolation process; (b) obtaining an image of the photoluminescence emitted from said solar cell or solar cell precursor as a result of said illumination; and (c) analysing the relative intensity of photoluminescence emitted from peripheral portions of said solar cell or solar cell precursor to obtain a measure of the effectiveness of said edge isolation process.

35. A method as claimed in claim 34, wherein said method further comprises the step of: (d) comparing said image with a corresponding photoluminescence image obtained before said edge isolation step.

36. A method for monitoring the progress of an edge isolation process in a solar cell production line, said method comprising the steps of: (a) applying an illumination to a solar cell precursor at a first time in said edge isolation process; (b) detecting photoluminescence emitted from said solar cell precursor as a result of said illumination, to obtain a first photoluminescence level; (c) repeating steps (a) and (b) for said solar cell precursor at a second, later time in said edge isolation process, to obtain a second photoluminescence level; and (d) comparing said first and second photoluminescence levels.

37. A method as claimed in claim 36, wherein step (a) is performed before the commencement of said edge isolation process.

38. A method as claimed in any one of claims 33 to 37, wherein said illumination has an intensity of less than or equal to one Sun.

39. A system when implementing the method of any one of claims 33 to 38.