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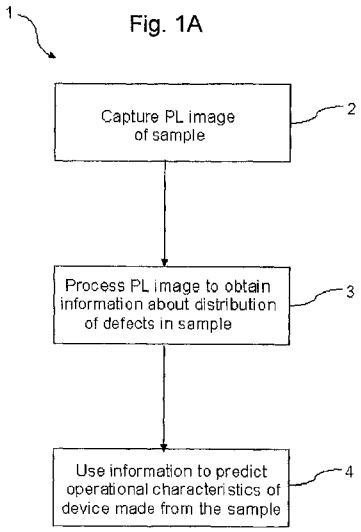

(57) Abstract: A method (1) is disclosed whereby luminescence images are captured (2) from as-cut or partially processed bandgap materials such as multicrystalline silicon wafers. These images are then processed (3) to provide information about defects such as dislocations within the bandgap material. The resultant information is then utilised (4) to predict various key parameters of a solar cell manufactured from the bandgap material, such as open circuit voltage and short circuit current. The information may also be utilised to apply a classification to the bandgap material. The methods can also be used to adjust or assess the effect of additional processing steps, such as annealing, intended to reduce the density of defects in the bandgap materials.

Wafer Imaging and Processing Method and Apparatus

Field of the Invention

[001] The present invention relates to the field of processing luminescence images acquired from direct and indirect bandgap semiconductor materials such as silicon wafers. In particular it relates to methods and apparatus for analysing luminescence images of wafers to obtain information about defects in the wafer material. This information may be used to classify the wafers or to predict operational characteristics of devices made from them.

Background of the Invention

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

[003] Most commercial photovoltaic cells (in particular solar cells) today are made from typically 10x10 cm^2 up to 21x21 cm^2 multicrystalline (mc) silicon wafers which are cut from a cast multicrystalline silicon block. The main processing steps on forming a solar cell after cutting the silicon wafer in the most widely adopted screen printed solar cell process are: 1) surface damage etch, 2) texturing, 3) diffusion, 4) SiN deposition, 5) screen printing of metal contacts, 6) firing, 7) edge isolation, and 8) electrical characterisation and binning. More sophisticated solar cell concepts use so-called selective emitter structures in which highly doped local areas are formed under metal contacts. Other advanced cell concepts use point contacts on the rear to improve the rear surface recombination. Normally, the electrical performance of a cell is measured only towards or at the end of the production process.

[004] The initial wafers are normally produced by sawing a large cast silicon block (also known as an ingot, typically up to 1x1x0.7 m^3 in size) into square (10x10 cm^2 up to 21x21 cm^2) shaped columns (also known as bricks), which are then wire sawn into individual wafers (each typically 150-300 µm thick). Currently, some wafer manufacturers use minority carrier lifetime measurements such as quasi steady state photoconductance or photoconductance decay measurements along the edge of the square block or brick to obtain information about the local material quality. One or several line-scans within the wafer area of individual wafers can also be used to assess the wafer quality. Normally, only limited two-dimensional information about lateral

variations of the material quality within each wafer is obtained. This is as a result of a high volume solar cell production line typically handling 1 wafer every one to three seconds, which limits the time available for characterisation.

[005] Some individual solar cell manufacturing processes such as screen printing and firing of electrical contacts can be performed as actual in-line processes, where the partially processed wafers are transported through the process one by one, typically on a belt. Other processes such as diffusion and SiN deposition are often carried out as batch processes with tens or hundreds of wafers being processed simultaneously.

[006] The average throughput of a typical silicon solar cell production line may be one solar cell every one to three seconds, which limits the time available for in-line characterisation of each sample. Existing spatially resolved measurements are generally too slow to yield high resolution two-dimensional information about the electronic wafer quality in such short timeframes. On the other hand it is known that small defects can have a large impact on device performance. High spatial resolution (<1mm per pixel) is thus required for a reliable characterisation. Manufacturers thus have limited tools that allow them to characterise the electronic properties of every wafer or of even a large fraction of wafers going through a production process with sufficiently high lateral spatial resolution.

[007] Certain materials that emit luminescence have a gap in their electronic density of states, the so-called bandgap. Such materials are referred to as bandgap materials. Direct and indirect bandgap semiconductors, including silicon, are included in this definition. Dislocations are a common type of structural defect in semiconductors such as silicon, and their presence strongly affects the electronic properties of the materials and consequently the performance of devices such as solar cells manufactured from them.

Summary of the Invention

[008] 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.

[009] In accordance with a first aspect, the present invention provides a method of conducting an analysis of a bandgap material, said method including the steps of:

(a) capturing a luminescence image of said bandgap material;

(b) processing said image to obtain information about defects in said bandgap material; and

(c) utilising said information to apply a classification to said bandgap material.

[0010] In a second aspect, the present invention provides method of conducting an analysis of a bandgap material, said method including the steps of:

(a) obtaining information about dislocation defects in said bandgap material; and

(b) utilising said information to apply a classification to said bandgap material.

[0011] In accordance with a third aspect of the present invention, there is provided a method of predicting one or more operational characteristics of a device fabricated from a bandgap material, said method including the steps of:

(a) obtaining at least one sample of said bandgap material;

(b) capturing luminescence image of said at least one sample;

(c) processing said image to obtain information about defects in said bandgap material from said sample;

(d) analysing one or more operational characteristics of a device fabricated from said sample; and

(e) correlating said operational characteristics with said information, wherein

(i) steps (b) and (c) are repeated for further samples of said bandgap material to obtain further information about the defects in said further samples; and

(ii) said further information is utilised to predict operational characteristics of devices fabricated from said further samples.

[0012] Preferably, the processing of the image includes enhancing the image by any suitable technique known in the art.

[0013] The information obtained preferably includes information about dislocation defects of the substrate material. More preferably, the information includes a measure of the density of dislocation defects across the material.

[0014] The processing of the image may include determining an absolute or relative area average of the dislocation density or a metric that is correlated with the dislocation density. The processing may also include a weighting function based on the position of the dislocation in relation for example to the metal contacts of a solar cell. The processing may also include a weighting function of the severity of a defect as apparent, for example, in its impact on the effective minority carrier lifetime.

[0015] The bandgap substrate material can comprise silicon. In one embodiment, the bandgap substrate material can comprise a multicrystalline silicon wafer and the step (c) can preferably include determining the likely operational characteristics of semiconductor devices which utilise the silicon wafer material as their substrate. In another embodiment, the bandgap substrate material can comprise a cast monocrystalline silicon wafer.

[0016] The silicon wafer can be an as-cut unprocessed silicon wafer or a partially processed silicon wafer.

[0017] The semiconductor device can comprise a photovoltaic cell.

[0018] The image processing can comprise the step of normalising the image with respect to the background doping concentration.

[0019] Specific defects, particularly dislocations, often appear with very similar spatial distribution in wafers from nearby regions in the same brick, in other words, the spatial distribution varies very little between several neighbour wafers. The embodiments can also include the step of performing the method on a single or on multiple wafers cut from adjacent or nearby slices of a silicon block or silicon brick and interpolating or extrapolating the results to determine the likely operational characteristics of devices made on other adjacent or nearby wafers. This may allow performance predictions on a larger sample set from measurements on only a subset of samples.

[0020] The method can also include the step of locating low material quality regions caused by edge defects or impurities along an edge of the wafer material.

[0021] The method can further include the step of: (d) utilising the results of the analysis step to alter parameters associated with a series of processing steps in the formation of a solar cell so as to improve the quality of the solar cell. The parameters can include the conditions for firing a metal pattern into the silicon wafer. The parameters can also include the diffusion conditions for diffusing materials into the silicon wafer.

[0022] In certain embodiments, the parameters include the diffusion conditions for diffusing material in to said bandgap material, or parameters for any other process that creates doped regions in said material.

[0023] In alternative embodiments, the method can also include the step of normalising the photoluminescence images with respect to the background doping of the wafer. The normalising step consists of dividing the luminescence intensity in each pixel by the background doping concentration.

[0024] In other embodiments, the processing can include various options including weighting the area sum or area average of dislocation densities or relative distribution of dislocation density for the location of said dislocation defect relative to the gridlines or metal contacts of a voltaic cell and/or according to the severity of the dislocation defects.

[0025] The information can be obtained using photoluminescence, microwave photoconductants decaying, optical transmission or optical reflection measurements. In some cases where optical transmission or optical reflection measurements are used, it is conducted in the 1,400nm–1,700nm spectral range.

[0026] As discussed below, the abovementioned methods are suitable for a range of bandgap materials and devices but are preferably designed to predict the operational characteristics of a photovoltaic cell including open circuit voltage, short circuit density, fill factor or efficiency.

[0027] In accordance with a fourth aspect of the present invention, there is provided a method of predicting one or more operational characteristics of a device fabricated from a bandgap material, said method including the steps of:

(a) obtaining at least one sample of said bandgap material;

(b) obtaining information about dislocation defects in said at least one sample;

(c) analysing one or more operational characteristics of a device fabricated from said at least one sample; and

(d) correlating said operational characteristics with said information, wherein

(i) step (b) is repeated for further samples of said bandgap material to obtain further information about dislocation defects in said further samples; and

(ii) said further information is utilised to predict said operational characteristics of devices fabricated from said further samples.

[0028] In accordance with a fifth aspect of the present invention, there is provided a method of predicting one or more operational characteristics of a device fabricated from a bandgap material, said method including the steps of:

(a) obtaining at least one sample of said bandgap material;

(b) obtaining information about dislocation defects in said at least one sample;

(c) utilising said information to apply a classification to said bandgap material;

(d) analysing one or more operational characteristics of a device fabricated from said at least one sample; and

(e) correlating said operational characteristics with said classification wherein

(i) steps (b) and (c) are repeated for further samples of said bandgap material to obtain a further classification for each of said further samples; and

(ii) said further classification is utilised to predict said operational characteristics of the devices fabricated from said further samples.

[0029] In the preferred embodiments the classification can also be used to reject, price and/or bin the bandgap material into different quality categories, or predict the operational characteristics of devices fabricated from said bandgap material.

[0030] A sixth aspect of the present invention provides a method of conducting an analysis of a silicon wafer material, said method including the steps of:

(a) capturing a photoluminescence image of said silicon wafer material;

(b) processing said image to obtain information about defects in said material; and

(c) utilising said information to apply a classification to said silicon wafer material.

[0031] In a seventh aspect, the present invention provides a method of predicting one or more operational characteristics of a device fabricated from a silicon wafer, said method including the steps of:

(a) obtaining at least one silicon wafer sample;

(b) capturing a luminescence image of said at least one sample;

(c) processing said image to obtain information about defects in said at least one sample;

(d) analysing one or more operational characteristics of a device fabricated from said at least one sample; and

(e) correlating said operational characteristics with said information, wherein

(i) steps (b) and (c) are repeated for further silicon wafer samples to obtain further information about the defects in said further samples; and

(ii) said further information is utilised to predict the operational characteristics of devices fabricated from said further samples.

[0032] In an eighth aspect, the present invention provides a system for conducting an analysis of a bandgap material, said system including:

an image capture device for capturing a luminescence image of said bandgap material;

an image processor for processing said image to obtain information about defects in said material, and;

a classifier for utilising said information to apply a classification to said bandgap material.

[0033] In a ninth aspect, the present invention provides a system for conducting an analysis of a bandgap material, said system including:

an acquisition device for obtaining information about dislocation defects in said bandgap material; and

a classifier for utilising said information to apply a classification to said bandgap material.

[0034] In a tenth aspect, the present invention provides a system for predicting one or more operational characteristics of a device fabricated from a bandgap material, said system including:

(a) an image capture device for capturing luminescence images of at least one sample of said bandgap material;

(b) an image processor for obtaining information about defects in said at least one sample;

(c) an analyser for analysing one or more operational characteristics of a device fabricated from said at least one sample;

(d) a correlator for obtaining a correlation between said operational characteristics and said information; and

(e) a predictor for predicting the operational characteristics of devices fabricated from further samples of said bandgap material, based on said correlation and on information about said defects obtained from said further samples.

[0035] In an eleventh aspect, the present invention provides a system for predicting one or more operational characteristics of a device fabricated from a bandgap material, said system including:

(a) an acquisition device for obtaining information about dislocation defects in at least one sample of said bandgap material;

(b) an analyser for analysing one or more operational characteristics of a device fabricated from said at least one sample;

(c) a correlator for obtaining a correlation between said operational characteristics and said information; and

(d) a predictor for predicting the operational characteristics of devices fabricated from further samples of said bandgap material, based on said correlation and on information about dislocation defects obtained from said further samples.

[0036] In a twelfth aspect, the present invention provides a method for distinguishing dislocation defects from grain boundaries in a multicrystalline silicon wafer, said method including the steps of: capturing a luminescence image of said silicon wafer; capturing a conventional optical image of said silicon wafer; and comparing said luminescence and optical images.

[0037] In a thirteenth aspect, the present invention provides a system for distinguishing dislocation defects from grain boundaries in a multicrystalline silicon wafer, said system including: a first image capture device for capturing a luminescence image of said silicon wafer; a second image capture device for capturing a conventional optical image of said silicon wafer; and a comparator for comparing said luminescence and optical images.

[0038] In a fourteenth aspect, the present invention provides a method for monitoring a process for reducing the density of defects in a bandgap material, said method including the steps of:

(a) capturing a photoluminescence image of said material before said process;

(b) processing said image to obtain a first measurement of the density of said defects in said material;

(c) capturing a photoluminescence image of said material after said process;

(d) processing said image to obtain a second measurement of the density of said defects in said material; and

(e) comparing said first and second measurements.

[0039] In a fifteenth aspect, the present invention provides a method for controlling a process for reducing the density of defects in a bandgap material, said method including the steps of:

(a) capturing one or more photoluminescence images of said material before said process, or after said process, or both;

(b) processing said images to obtain one or more measurements of the density of said defects in said material; and

(c) adjusting one or more conditions of said process based on said one or more measurements.

[0040] In a sixteenth aspect, the present invention provides a system for monitoring a process for reducing the density of defects in a bandgap material, said system including: an image capture device for capturing photoluminescence images of said material before and after said defect reduction process; an image processor for processing said images to obtain measurements of the density of said defects in said material before and after said defect reduction process; and a comparator for comparing said measurements.

[0041] In a seventeenth aspect, the present invention provides a system for controlling a process for reducing the density of defects in a bandgap material, said system including: an image capture device for capturing photoluminescence images of said material before and/or after said defect reduction process; an image processor for processing said images to obtain measurements of the density of said defects in said material before and/or after said defect reduction process; and a controller for adjusting one or more conditions of said process based on at least one of said measurements.

Brief Description of the Drawings

[0042] A preferred embodiment of the invention will now be described, by way of example only, with reference to the accompanying drawings in which:

Fig. 1A illustrates the steps in a preferred embodiment;

Fig. 1B illustrates the steps in another preferred embodiment;

Fig. 2 illustrates a photoluminescence image of a multicrystalline silicon wafer;

Fig. 3 illustrates a filtered version of the image shown in Fig. 2;

Fig. 4 illustrates a filtered photoluminescence image of a raw multicrystalline silicon wafer;

Fig. 5 illustrates a high pass filtered photoluminescence image of a fully processed solar cell made from a wafer adjacent to the wafer of Fig. 4;

Fig. 6 illustrates a spectral Light Beam Induced Current (LBIC) map of the solar cell of Fig. 5;

Fig. 7 illustrates a correlation between dislocation density in raw wafers and open circuit voltage in finished cells made from neighbouring wafers;

Fig. 8 illustrates a photoluminescence image of a 'boundary' wafer, i.e. a wafer cut from a region close to the edge of an ingot;

Fig. 9 illustrates photoluminescence images of neighbouring wafers to the wafer of Fig. 8; and

Fig. 10 illustrates a production line process for utilisation of the preferred embodiment.

Description of the Preferred and Other Embodiments

[0043] Lateral variations in the electronic material quality of the substrate material (for example a silicon wafer) can have a large impact on key performance parameters of solar cells manufactured from the material, such as open circuit voltage, short circuit current density, fill factor and efficiency.

[0044] The preferred embodiment provides methods and systems that can rapidly assess the quality of raw wafers at the start of solar cell manufacturing or at the end of wafer manufacturing and predict cell performance parameters or statistical variations thereof expected under normal processing conditions. The methods and systems can also be used to assess the effect of additional processing steps, such as annealing, intended to improve the electronic material quality.

[0045] The preferred embodiment includes analysis of photoluminescence (PL) images of a bandgap material, i.e. images of band-to-band recombination luminescence generated by photo-excitation of the material. In alternative embodiments the luminescence may be generated by other means, such as electrical excitation (electroluminescence). PL imaging is a fast and contact-less metrology technique for silicon wafer characterisation, disclosed for example in published US patent application 2009/0051914 A1, the contents of which are incorporated by reference. PL imaging can be conducted on as-cut mc-silicon wafers with high spatial resolution and a total data acquisition time of about one second per wafer.

[0046] The preferred embodiment has particular application to the characterisation of raw or partially processed silicon wafers, including assessing the absolute or relative density distributions of defects such as dislocations, and the subsequent prediction of solar cell parameters including open circuit voltage, short circuit current density, fill factor and efficiency. The present description concentrates on determining the distribution density of dislocations, but the inventive concepts also apply to analysis of other defects that can result in degraded cell performance, including impurities, cracks and shunts.

[0047] Based on this information on the defect density distribution a wafer can be classified or priced, with the following benefits:

1) Wafer manufacturers can use the information to assess the quality of their outgoing material (the wafers) so that they can demonstrate to their customers (cell manufacturers) that they delivered wafer quality that meets the specification, or they can price their product according to the product quality;

2) Cell manufacturers can use the information in the opposite way, i.e. to check that the wafers received from the wafer manufacturer meet the required quality specification.

3) Wafer manufacturers can systematically use PL images on raw or partially processed wafers to determine the distribution of dislocations in three dimensions (i.e. across the area of wafers and down through the brick from which the wafers were cut). This information may be fed back into the processing conditions for block casting, to improve the manufacturing process.

4) Cell manufacturers can use wafer binning to sort wafers. Because different optimum processing conditions exist for wafers with variable amounts of dislocations, the wafers may then be processed with optimised bin-specific processing conditions. Further, variations to the processing may be achieved to effect a higher quality outcome, e.g. a wafer may be rotated to ensure that a specific high defect zone is not near the bus bars of an as-completed cell. In modern cell concepts such as semiconductor finger technology where a laser is used to define highly laterally conductive current paths, the laser could be guided to avoid dislocation or impurity-rich regions.

5) Cell manufacturers may also reject wafers with insufficient material quality.

6) Cell manufacturers may also use the wafer binning to assign wafers to specific solar cell processing lines. That assignment can include assigning to different solar cell lines processing the same type of solar cell but with different processing parameters in different lines, or to different cell lines producing different types of solar cells.

7) The defect distribution parameters as determined from a PL image can become standard parameters for wafer quality.

8) Over time, a large database of analysis can be built up so as to provide improved image analysis results and improved algorithms for binning/sorting.

[0048] The steps involved in one preferred embodiment involve the capture and processing of photoluminescence images from bandgap materials such as silicon, and using the results of the processing to predict operational characteristics of devices, such as photovoltaic (solar) cells, fabricated from the materials. The steps 1 are illustrated in Fig. 1A and include a first step 2 of capturing a photoluminescence image followed by processing 3 of the captured image, firstly to enhance the image to highlight those defects such as dislocations, that may be present in the sample, and secondly to obtain information about the distribution of those defects. This information may include an absolute or relative area average of the defect density or a metric that is correlated with the defect density or with the defect distribution or both. Finally, in step 4 the information is used to predict operational characteristics of devices, such as solar cells, made from the material.

[0049] The steps involved in another preferred embodiment involve the capture and processing of photoluminescence images from bandgap materials such as silicon, and using the results of the processing to classify the materials. The steps 5 are illustrated in Fig. 1B and include a first step 2 of capturing a photoluminescence image followed by processing 3 of the captured image, firstly to enhance the image to highlight those defects such as dislocations that may be present in the sample, and secondly to obtain information about the distribution of those defects. This information may include an absolute or relative area average of the defect density or a metric that is correlated with the defect density or with the defect distribution or both, and is used to assign a figure of merit to the sample. Finally, in step 6 this figure of merit is used to classify the sample, e.g. for binning or pricing purposes. It will be appreciated that while operational characteristics of subsequent devices cannot be predicted with absolute accuracy, it is sufficient for binning or pricing purposes to know that solar cells made from bandgap statistical correlations between the results of the processing 3 of the captured image and specific solar cell characteristics. It is also possible for samples to be classified on the basis of a prediction of operational characteristics of devices that would be made from material with a higher dislocation density will, on average, have inferior properties.

[0050] PL image capture is known and is, for example, disclosed in 'Progress with luminescence imaging for the characterisation of silicon wafers and solar cells', 22nd European Photovoltaic Solar Energy Conference, Milano, Italy, September 2007, the contents of which are hereby incorporated by cross reference.

[0051] Fig. 2 shows an example of a PL image 10 of a 1Ωcm p-type 15x15 cm^2 mc-silicon wafer as would be typically used in solar cell manufacturing. This image reveals a strong variation of the material quality, i.e. bright areas 11 correspond to areas with good electronic properties and darker areas 12 correspond to areas with poorer electronic properties. Note that in the PL imaging applications discussed here we refer to measurements of the band-to-band luminescence, which occurs during radiative recombination between electrons in the conduction band and holes in the valence band of a semiconductor. In silicon the majority of photons emitted during that process are in the spectral range 850nm to 1300nm at room temperature.

[0052] The PL image 10 was taken on an as-cut 15x15cm^2 mc-Si wafer. Further analysis discloses that the image has two dominating features: 1) a long range variation with higher luminescence intensity in the centre 11 and lower intensity towards the edges 12; and 2) short range variations 13 of lower intensity. The latter patterns are interpreted as dislocation clusters. Some individual lines may also be caused by recombination-active grain boundaries.

[0053] The next step 3 in the method of the preferred embodiment is to process the PL image. A variety of standard image processing techniques exist that allow filtering or enhancing of specific predetermined image features, which in the present application are characteristic for example of certain types of defects that can degrade solar cell performance. Common types of image processing techniques, amongst others, include noise reduction (median filtering, wavelet domain methods, bilateral filtering, grey scale morphological reconstruction), line detection (for example using edge detection techniques such as Sobel-edge detection), and image deconvolution (Weiner filtering, blind deconvolution, iterative deconvolution via the Lucy-Richardson and Landweber method). These techniques are described in standard texts such as 'Digital Image Processing' by R. Gonzalez and R. Woods (3rd ed, 2008).

[0054] 'High pass filtering' is a generic term for a filtering process that removes low frequency components of an image or some other signal or data set. In the present context, high pass filtering can be used to remove the influence of the long range luminescence variations from a PL image. Fig. 3 illustrates an example result 20 of the PL image of Fig. 2 image processed with a high pass filter that eliminates long range variations, so that the distribution of small scale variations 21, caused for example by dislocations or recombination active grain boundaries, is revealed more clearly. By way

of example only, a simple form of high pass filtering consists of applying a Fast Fourier Transform (FFT) to the original image, eliminating low spatial frequencies from the resulting frequency domain image, and applying an inverse FFT.

[0055] In alternative embodiments, further image processing steps can be applied to the image. In one example, the image itself may be normalised with respect to a background doping level for improved results. The background dopant may for example be boron for p-type silicon or phosphorus for n-type silicon. In another example, image contrast may be enhanced by one of the abovementioned image deconvolution techniques, taking into account a theoretical or experimentally measured point spread function of the system. Point spread effects are generally caused by non-ideal optics, and in the case of luminescence imaging using a CCD camera, can also be caused by lateral scattering of light within the CCD chip. In the context of dislocations, deconvolution algorithms can greatly enhance the image contrast between dislocations or other local features and the background.

[0056] Once a PL image has been enhanced, say by a combination of filtering and deconvolution techniques, to highlight dislocations in the material, the image processing may continue with one or more algorithms, such as Sobel-edge detection, for obtaining information about the distribution density of the dislocations.

[0057] Distinguishing dislocations from grain boundaries in PL images of mc-silicon can be difficult in practice. Comparison of PL images with conventional optical images can be useful in this context, because optical images show grain boundaries but not dislocations, allowing the two types of feature to be distinguished.

[0058] Specific defects, particularly dislocations, often appear with very similar spatial distribution in wafers from nearby regions in the same brick, in other words, the spatial distribution varies very little between several neighbour wafers. Fig. 4 shows a PL image 40 of a raw wafer after high pass filtering, Fig. 5 shows a PL image 50 of a finished cell made from a neighbouring wafer, and Fig. 6 illustrates a corresponding diffusion length image obtained from a spectral Light Beam Induced Current (LBIC) map taken on the same cell. A strong correlation is observed between the LBIC data (Fig. 6) and the PL image on the neighbouring raw wafer (Fig. 4). Hence the filtered PL image of a cell can act as a proxy for the LBIC image, and a filtered PL image of a raw wafer can be used as an indicator of the likely operational condition of a cell made from that wafer or from wafers cut from adjacent portions of a brick. This allows

performance predictions to be made for a larger sample set, from measurements on only a subset of wafer samples.

[0059] The LBIC data in Fig. 6 representing regions with low minority carrier diffusion length correspond to regions in which the collection of photo-generated carriers is relatively lower, which tends to have a direct impact on the short circuit current density of the cell. The correlations found between the data of Fig. 4 and Fig. 6 suggest that the PL image on a raw wafer correlates well with the short circuit current density in a finished cell. In a similar fashion, Fig. 7 shows a correlation between the average dislocation density in raw wafers, obtained as described above from PL imaging, and the open circuit voltage of solar cells manufactured from "sister" (neighbouring) wafers. In particular, it can be seen that lower dislocation densities correlate with higher open circuit voltages, so that the dislocation density observed in raw or partially processed wafers can be used to predict cell voltage.

[0060] In a simple approach the average absolute or relative density of defected regions (regions with dislocations) across a PL image taken at an early stage of solar cell processing may be correlated with cell parameters such as short circuit current density, open circuit voltage, fill factor or efficiency (as shown in Fig.7). More sophisticated algorithms can use weighting functions based on the position of the defect, e.g. the proximity to the metal contacts, (e.g. grid lines or busbars) or the edges of the cell. For example a defect that is close to a busbar or one of the metal fingers is likely to have a bigger impact on the cell voltage than a defect that is located further away from the busbar.

[0061] The darker a defect appears in a photoluminescence image, the stronger is its recombination activity. A weighting function may also be based on the relative intensity variation of the luminescence intensity in a defected region.

[0062] The luminescence intensity is normally proportional to the background doping, which varies in a well known way from the bottom of an ingot to the top. Thus, if the background doping is known (either from the known position of the wafer in the ingot, or via a separate measurement), then the luminescence intensity may be normalised to the doping level, allowing a more quantitative comparison of the luminescence intensity from different wafers. The normalisation can involve dividing the measured luminescence image by a constant factor that is equivalent or proportional to the average

background doping concentration across the wafer, itself corresponding in a generally non-linear fashion to the wafer's position in the ingot.

[0063] The PL imaging techniques disclosed can not only be used on raw wafers and on finished cells but on wafers at any of the processing stages in solar cell production.

[0064] It is known that the density of dislocations in silicon wafers or silicon bricks can be reduced by a thermal annealing process (K. Hartman *et al* 'Dislocation density reduction in multicrystalline silicon solar cell material by high temperature annealing', *Applied Physics Letters* vol 93(12) 122108 (2008)). On wafers such a process could be used by wafer manufacturers or by solar cell manufacturers to mitigate the impact of dislocations on cell performance, and wafer manufacturers may also be able to anneal entire bricks. The annealing process could be performed as a batch process or as a continuous in-line process, at a temperature between 1200 and 1400 degrees Celsius. In principle the process can be performed on any type of silicon wafer, but is most useful for silicon samples known to contain dislocations, i.e. multicrystalline silicon wafers (which includes both string ribbon and edge-defined film-fed growth (EFG) wafers) and cast monocrystalline wafers.

[0065] Since PL measurements enable rapid assessment of the absolute or relative areal dislocation density and the spatial distribution of dislocation affected areas (i.e. the absolute or relative distribution of dislocation densities), PL imaging can be used to monitor this thermal annealing process. For example PL imaging performed on a sample before and after annealing would allow quantitative assessment of the efficacy of the annealing process. If individual sample tracking is not possible, an analysis could be performed based on statistical data for dislocation densities from a number of samples, calculated from PL images obtained before and after the annealing step.

[0066] Such process monitoring could also result in improved process control, where the annealing conditions are adjusted based on the results from PL image analysis. This process control could be performed automatically, based on predetermined algorithms or empirical data. These annealing conditions may for example be the temperature profile (heating the sample to a desired temperature, keeping it at one or more constant temperatures and finally cooling the sample to room temperature), or the atmosphere in the annealing furnace. Optimal process conditions for annealing may also depend on the dislocation density itself, so that the results of a pre-anneal PL measurement may be used to determine optimal annealing conditions. This may be combined with sorting

wafers into separate quality bins to allow processing individual bins with given annealing conditions.

[0067] A PL image measured prior to an annealing may also be used to classify wafers into wafers with low dislocation density versus wafers with high dislocation density, allowing selection of wafers with low dislocation density which do not require the annealing step, thereby reducing the total amount of wafers that have to go through the additional annealing step and resulting in optimised operation in wafer or cell production.

[0068] While PL imaging of band-to-band recombination luminescence is our preferred method for analysing the distribution density of dislocations in silicon, it is not the only method. Under certain processing and excitation conditions, dislocations in silicon have been demonstrated to emit light in the 1400nm – 1700nm spectral range (I. Tarasov *et al*, 'Defect passivation in multicrystalline silicon for solar cells', *Applied Physics Letters* vol 85(19), 4346-4348 (2004)). According to a generalisation of Kirchhoff's law, which is applicable to luminescence, any material that has the ability to absorb light in a specific wavelength range can also emit light in that same range, and vice versa. Dislocation-rich regions in a silicon wafer should therefore absorb more strongly in the 1400nm – 1700nm spectral range than regions with zero or low dislocation density. In one embodiment, reflectance or transmission measurements limited to that spectral range are used to identify dislocations in silicon. These reflectance or transmission measurements can be performed in a spatially resolved fashion using line-scan or area cameras that are sensitive in the 1400nm - 1700nm spectral range, in combination with suitable narrow spectrum or suitably filtered light sources.

[0069] Apart from dislocations, another example of a specific type of defect that can be identified in starting wafer material (i.e. as-cut wafers) by luminescence imaging are impurity-related defects near the edge of a wafer that result in low carrier lifetime and therefore reduced cell efficiency. As-cut multicrystalline wafers often have low material quality around the edges or in the corners, originating from high impurity concentrations at the bottom, top and side walls of the cast multicrystalline block from which the wafers were cut. These impurities often arise from diffusion of oxygen and transition metals or other metals from the crucible walls into the silicon block during the casting and crystallisation process. At the top of a block, the low carrier lifetime is caused by segregated impurities such as transition metals and carbon which 'float' to the top during

the crystallisation, which normally proceeds from the bottom of a block to the top. These low carrier lifetime regions at the bottom, top and sides of a block are normally cut off by the wafer manufacturer before the block is chopped up into bricks, so that ideally only good quality regions are used for wafer production. Often however wafer manufacturers do not cut off enough material, so that very low carrier lifetime material is found in some wafers near an edge or near one corner.

[0070] Fig. 8 illustrates an example PL image of a wafer that was cut from the edge of a block (left). In the high impurity/low lifetime regions, which appear generally dark in the PL image, defects such as dislocations and grain boundaries appear brighter instead of darker. This contrast reversal occurs because of gettering of impurities by the dislocations, which improves the material quality in their vicinity. These 'bright' dislocations appear more diffused than the 'dark' dislocations of low impurity regions, but similar line detection algorithms can still be used to highlight the dislocations and measure their areal density.

[0071] In certain embodiments, the PL imaging can thus be used to identify

1) Wafers from the bottom or top of an ingot.
2) Wafers from the edge or corners of an ingot.

Image processing of the PL images can result in the automatic identification and classification of certain features. Classification may be based for example on the severity of the defect, the latter detectable for example in PL images by the luminescence intensity, or on the affected area, or combinations thereof. Wafer and cell manufacturers may thus use PL imaging to sort these wafers out or bin them into various quality bins, and cell manufacturers can reject such wafers and send them back to the wafer manufacturer or pay a lower price.

[0072] An example is shown in Fig.9, where four neighbouring wafers were PL imaged (a) after surface damage etch, (b) after emitter diffusion, (c) after SiN deposition and (d) after full cell processing. The dislocation clusters that are visible in the finished cell (d) are clearly observed after the diffusion step (b). While the dislocations are also detectable by PL on as-cut wafers, measuring after the diffusion step can be advantageous as the PL intensity is generally enhanced after that step allowing shorter data acquisition, lower quality equipment or resulting in higher spatial resolution images or any combination thereof. The enhanced photoluminescence signal is a result of the field effect surface passivation on the emitter diffused side.

[0073] In one embodiment the binning and sorting and dedicated processing procedures may be applied after the emitter diffusion step. Further, it is possible to adjust the processing steps, such as the firing conditions, based on the results from the PL images after the diffusion step, thereby providing improved end results.

[0074] Further modifications are possible. Wafer manufacturers could for example use the PL imaging technique not just on wafers but on entire blocks or on the individual square columns (bricks). For example every brick could be measured with PL imaging on one or more sides before it is sawn into wafers, allowing the wafer manufacturer to identify the position of low lifetime regions or to detect dislocation densities on the sides of the bricks, thereby gaining information about the dislocation density inside the ingot at a given height (i.e. at a specific wafer position) or about the position of low lifetime regions as caused by high impurity content. Combining several images will allow acquisition of more detailed and accurate information in that context. Wafer manufacturers may also measure the entire block to identify the best position to chop off the impurity-rich sides, bottom and top.

[0075] When a 'brick' from which wafers are sliced is measured, speed is not as crucial as for measuring individual wafers. Normally, a brick is sawn into a few hundred wafers so that there is more time available for characterisation. A line scanning PL tool can therefore be employed where the illumination is in a line shape and a linear detector array is used to capture the emission. Alternatively a series of two-dimensional images can be taken on various parts on the ingot or block in a mapping-style arrangement, thereby generating a high resolution image of the entire ingot or block.

[0076] Turning to Fig. 10, there is illustrated schematically an example production line system for the manufacture of solar cells utilising the method of the preferred embodiment. In this system wafers are transported along a belt where they are imaged by a PL capture system. The resulting images are processed and analysed before display and storage.

[0077] The utilisation of the preferred embodiments can be extended to both monocrystalline and multicrystalline wafers. Multicrystalline wafers are normally manufactured using a casting process. Different methods exist for manufacturing monocrystalline silicon wafers, including the 'Czochralsky method' (Cz) and the 'float zone' method. In terms of cell efficiencies, monocrystalline silicon is generally preferable over multicrystalline silicon, however the higher solar cell efficiencies are

normally offset by the higher cost of producing monocrystalline wafers. Recently a method for manufacturing cast monocrystalline silicon wafers has been introduced and details of the method can be found in United States Patent Application Publication 2007/0169684 A1 in the name of Stoddard et al. A general advantage of conventional monocrystalline silicon wafers is that they have lower impurity concentrations compared to multicrystalline wafers and can be essentially free from structural defects such as dislocations or grain boundaries. In contrast dislocations can be present in the above mentioned cast monocrystalline wafers. The techniques of the preferred embodiment have equal application to unpassivated cast monocrystalline silicon wafers. Further, the density of structural defects as determined from a wafer by luminescence imaging at an early stage may be correlated with the current density and/or voltage or other cell parameters. In comparison with multicrystalline wafers the identification of the structural defects from luminescence images is significantly easier and more reliable in the case of a cast monocrystalline silicon wafer due to the absence of many other features commonly observed in luminescence images taken on multicrystalline wafers.

[0078] The preferred embodiment has direct application to other photovoltaic cell materials and can be utilised with other bandgap materials such as monocrystalline silicon, thin film silicon, CdTe, amorphous silicon , micro-morph silicon, nanocrystalline silicon on glass, copper indium gallium diselenide (CIGS) and related thin film materials.

[0079] Although the invention has been described with reference to specific examples it will be appreciated by those skilled in the art that the invention may be embodied in many other forms.

We Claim:

1. A method of conducting an analysis of a bandgap material, said method including the steps of:

(a) capturing a luminescence image of said bandgap material;

(b) processing said image to obtain information about defects in said bandgap material; and

(c) utilising said information to apply a classification to said bandgap material.

2. A method of conducting an analysis of a bandgap material, said method including the steps of:

(a) obtaining information about dislocation defects in said bandgap material; and

(b) utilising said information to apply a classification to said bandgap material.

3. A method of predicting one or more operational characteristics of a device fabricated from a bandgap material, said method including the steps of:

(a) obtaining at least one sample of said bandgap material;

(b) capturing a luminescence image of said at least one sample;

(c) processing said image to obtain information about defects in said at least one sample;

(d) analysing one or more operational characteristics of a device fabricated from said at least one sample; and

(e) correlating said operational characteristics with said information, wherein

(i) steps (b) and (c) are repeated for further samples of said bandgap material to obtain further information about the defects in said further samples; and

(ii) said further information is utilised to predict the operational characteristics of devices fabricated from said further samples.

4. A method of predicting one or more operational characteristics of a device fabricated from a bandgap material, said method including the steps of:

(a) obtaining at least one sample of said bandgap material;

(b) obtaining information about dislocation defects in said at least one sample;

(c) analysing one or more operational characteristics of a device fabricated from said at least one sample; and

(d) correlating said operational characteristics with said information, wherein

(i) step (b) is repeated for further samples of said bandgap material to obtain further information about dislocation defects in said further samples; and

(ii) said further information is utilised to predict said operational characteristics of devices fabricated from said further samples.

5. A method of predicting one or more operational characteristics of a device fabricated from a bandgap material, said method including the steps of:

(a) obtaining at least one sample of said bandgap material;

(b) obtaining information about dislocation defects in said at least one sample;

(c) utilising said information to apply a classification to said bandgap material;

(d) analysing one or more operational characteristics of a device fabricated from said at least one sample; and

(e) correlating said operational characteristics with said classification wherein

(i) steps (b) and (c) are repeated for further samples of said bandgap material to obtain a further classification for each of said further samples; and

(ii) said further classification is utilised to predict said operational characteristics of the devices fabricated from said further samples.

6. A method as claimed in claim 1 or claim 3, wherein said luminescence image is a photoluminescence image.

7. A method as claimed in any one of claims 1 to 5, wherein said information includes the area sum or area average of dislocation densities or the relative distribution of dislocations in said bandgap material.

8. A method as claimed in any one of claims 1 to 5, wherein said bandgap material comprises silicon.

9. A method as claimed in claim 8, wherein said bandgap material comprises an as-cut or partially processed multicrystalline or monocrystalline silicon wafer.

10. A method as claimed in claim 96, wherein said utilising step includes predicting the operational characteristics of a semiconductor device fabricated from said multicrystalline or monocrystalline silicon wafer.

11. A method as claimed in claim 10, wherein said semiconductor device comprises a photovoltaic cell.

12. A method as claimed in any one of claims 1 to 5, wherein said bandgap material comprises a block of silicon.

13. A method as claimed in any one of claims 1 to 5, further comprising the step of performing the method on one or more wafers cut from adjacent or nearby slices of an ingot or block of said bandgap material, and interpolating or extrapolating the results to predict the operational characteristics of devices fabricated from one or more neighbouring wafers cut from said ingot or block, or to apply a classification to said neighbouring wafers.

14. A method as claimed in claim 1 or claim 3, further or alternatively comprising the step of locating low material quality regions caused by edge defects or impurities along an edge of said bandgap material.

15. A method as claimed in any one of claims 1 to 5, further comprising the step of utilising the classification or predicted operational characteristics to alter parameters associated with a series of processing steps in the formation of a photovoltaic cell so as to improve the quality of said photovoltaic cell.

16. A method as claimed in claim 15, wherein said parameters include the conditions for firing a metal pattern into said bandgap material.

17. A method as claimed in claim 15, wherein said parameters include the diffusion conditions for diffusing materials into said bandgap material, or parameters for any other process that creates doped regions in said material.

18. A method as claimed in claim 1 or claim 3, further comprising the step of normalising said image with regard to the background doping level of said bandgap material.

19. A method as claimed in claim 7, wherein said area sum or area average of dislocation densities or said relative distribution of dislocations is weighted for the location of said dislocations relative to the grid lines or other metallic contacts of a photovoltaic cell.

20. A method as claimed in claim 7, wherein said area sum or area average of dislocation densities or said relative distribution of dislocations is weighted according to the severity of said dislocations.

21. A method as claimed in claim 20, wherein said severity is assessed based on the contrast in a luminescence image.

22. A method as claimed in claims 2, 4 or 5, wherein said information is obtained from said bandgap material by using photoluminescence, microwave photoconductance decay, optical transmission, or optical reflection measurements.

23. A method as claimed in claim 22, wherein said optical transmission or optical reflection measurements are performed in the 1400nm – 1700nm spectral range.

24. A method as claimed in any one of claims 3 to 5, wherein said device is a photovoltaic cell and said operational characteristics include the open circuit voltage, short circuit current density, fill factor or efficiency.

25. A method as claimed in claims 1, 2 or 5, wherein the classification of said bandgap material includes binning, rejecting, pricing or prediction of one or more operational characteristics of devices fabricated from said material.

26. A method of conducting an analysis of a silicon wafer material, said method including the steps of:

(a) capturing a photoluminescence image of said silicon wafer material;

(b) processing said image to obtain information about defects in said material; and

(c) utilising said information to apply a classification to said silicon wafer material.

27. A method of predicting one or more operational characteristics of a device fabricated from a silicon wafer, said method including the steps of:

(a) obtaining at least one silicon wafer sample;

(b) capturing a luminescence image of said at least one sample;

(c) processing said image to obtain information about defects in said at least one sample;

(d) analysing one or more operational characteristics of a device fabricated from said at least one sample; and

(e) correlating said operational characteristics with said information, wherein

(i) steps (b) and (c) are repeated for further silicon wafer samples to obtain further information about the defects in said further samples; and

(ii) said further information is utilised to predict the operational characteristics of devices fabricated from said further samples.

28. A system for conducting an analysis of a bandgap material, said system including:

an image capture device for capturing a luminescence image of said bandgap material;

an image processor for processing said image to obtain information about defects in said material; and

a classifier for utilising said information to apply a classification to said bandgap material.

29. A system for conducting an analysis of a bandgap material, said system including:

an acquisition device for obtaining information about dislocation defects in said bandgap material; and

a classifier for utilising said information to apply a classification to said bandgap material.

30. A system for predicting one or more operational characteristics of a device fabricated from a bandgap material, said system including:

(a) an image capture device for capturing luminescence images of at least one sample of said bandgap material;

(b) an image processor for obtaining information about defects in said at least one sample;

(c) an analyser for analysing one or more operational characteristics of a device fabricated from said at least one sample;

(d) a correlator for obtaining a correlation between said operational characteristics and said information; and

(e) a predictor for predicting the operational characteristics of devices fabricated from further samples of said bandgap material, based on said correlation and on information about said defects obtained from said further samples.

31. A system for predicting one or more operational characteristics of a device fabricated from a bandgap material, said system including:

(a) an acquisition device for obtaining information about dislocation defects in at least one sample of said bandgap material;

(b) an analyser for analysing one or more operational characteristics of a device fabricated from said at least one sample;

(c) a correlator for obtaining a correlation between said operational characteristics and said information; and

(d) a predictor for predicting the operational characteristics of devices fabricated from further samples of said bandgap material, based on said correlation and on information about dislocation defects obtained from said further samples.

32. A method for distinguishing dislocation defects from grain boundaries in a multicrystalline silicon wafer; said method including the steps of: capturing a

luminescence image of said silicon wafer; capturing a conventional optical image of said silicon wafer; and comparing said luminescence and optical images.

33. A system for distinguishing dislocation defects from grain boundaries in a multicrystalline silicon wafer, said system including: a first image capture device for capturing a luminescence image of said silicon wafer; a second image capture device for capturing a conventional optical image of said silicon wafer; and a comparator for comparing said luminescence and optical images.

34. A method for monitoring a process for reducing the density of defects in a bandgap material, said method including the steps of:

(a) capturing a photoluminescence image of said material before said process;

(b) processing said image to obtain a first measurement of the density of said defects in said material;

(c) capturing a photoluminescence image of said material after said process;

(d) processing said image to obtain a second measurement of the density of said defects in said material; and

(e) comparing said first and second measurements.

35. A method for controlling a process for reducing the density of defects in a bandgap material, said method including the steps of:

(a) capturing one or more photoluminescence images of said material before said process, or after said process, or both;

(b) processing said images to obtain one or more measurements of the density of said defects in said material; and

(c) adjusting one or more conditions of said process based on said one or more measurements.

36. A method as claimed in claim 34 or claim 35, wherein said bandgap material is silicon, said defects are dislocations, and said process is thermal annealing.

37. A system for monitoring a process for reducing the density of defects in a bandgap material, said system including: an image capture device for capturing

photoluminescence images of said material before and after said defect reduction process; an image processor for processing said images to obtain measurements of the density of said defects in said material before and after said defect reduction process; and a comparator for comparing said measurements.

38. A system for controlling a process for reducing the density of defects in a bandgap material, said system including: an image capture device for capturing photoluminescence images of said material before and/or after said defect reduction process; an image processor for processing said images to obtain measurements of the density of said defects in said material before and/or after said defect reduction process; and a controller for adjusting one or more conditions of said process based on at least one of said measurements.

39. A system as claimed in claim 37 or claim 38, wherein said bandgap material is silicon, said defects are dislocations, and said process is thermal annealing.

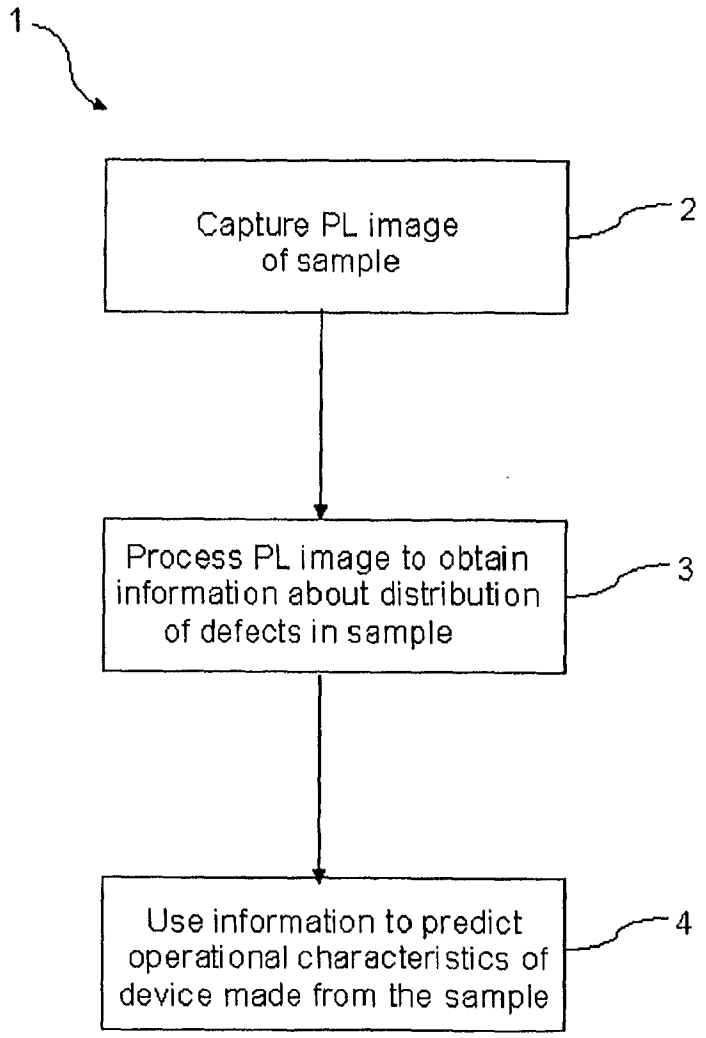
1
Capture PL image of sample
2
Process PL image to obtain information about distribution of defects in sample
3
Use information to predict operational characteristics of device made from the sample
4

Fig. 1A

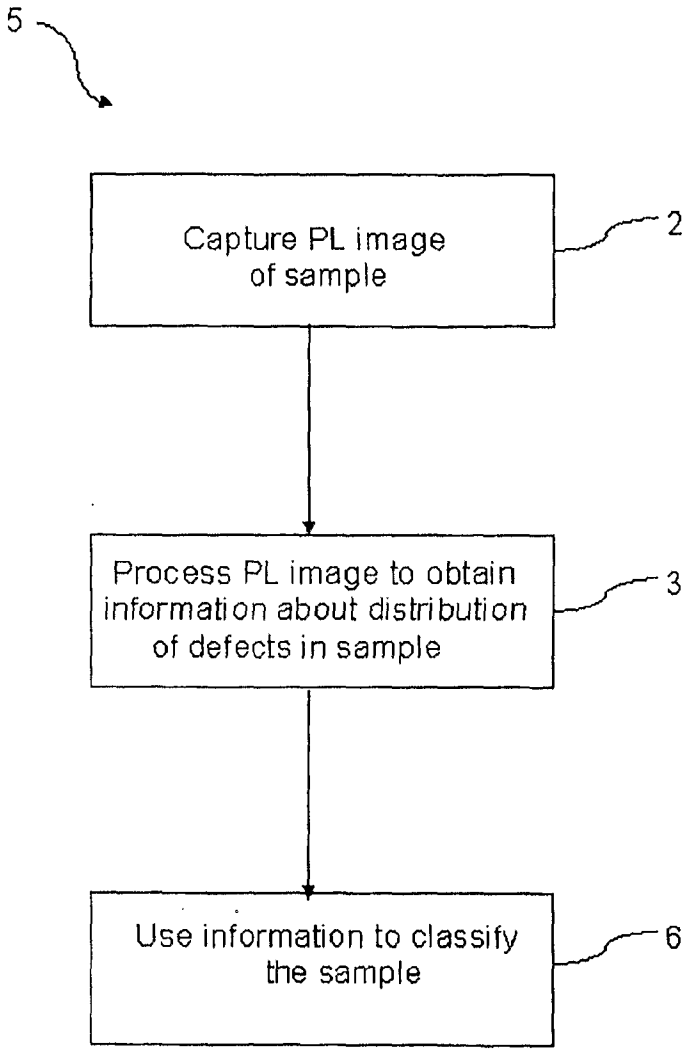
5
Capture PL image of sample
2
Process PL image to obtain information about distribution of defects in sample
3
Use information to classify the sample
6

Fig. 1B

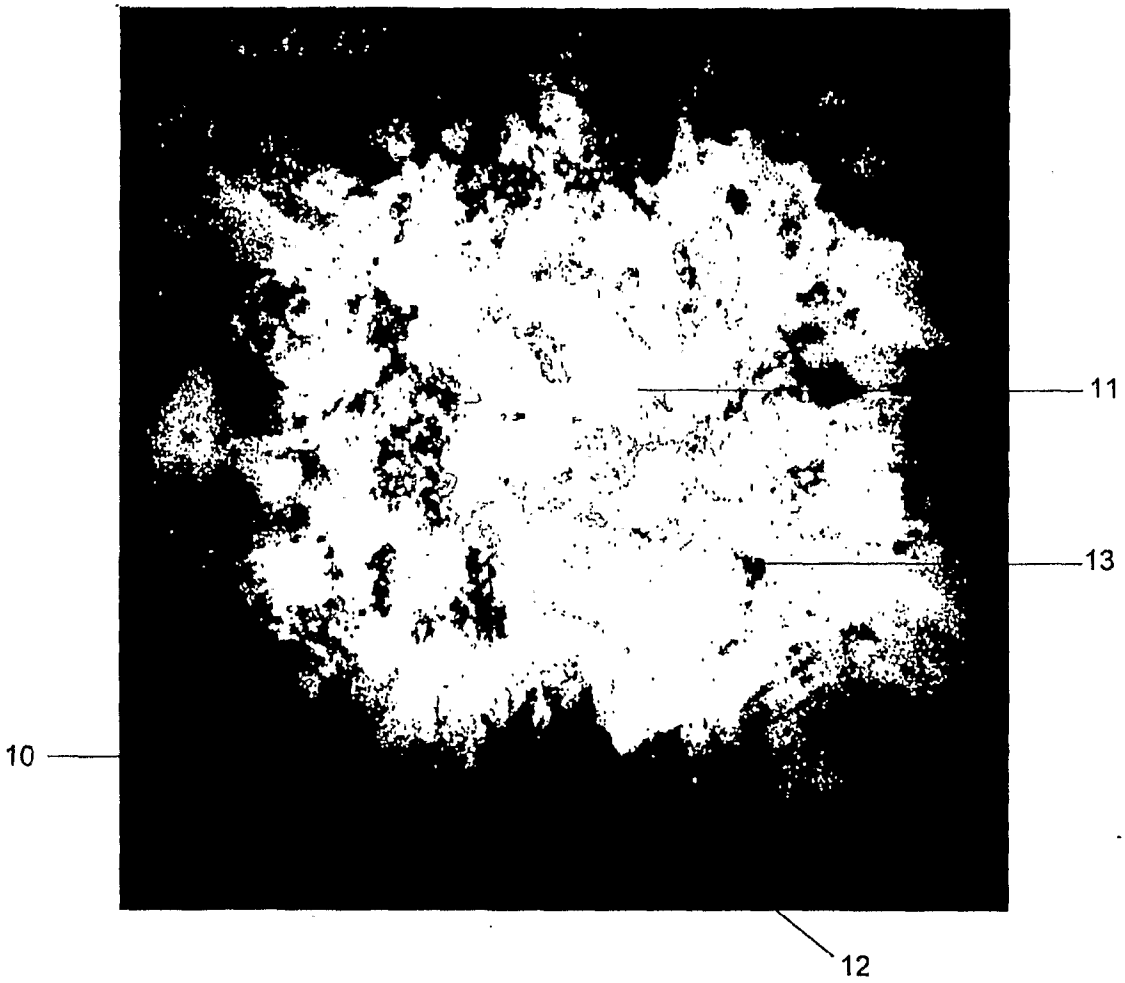

Fig. 2

Fig. 3

Fig. 4

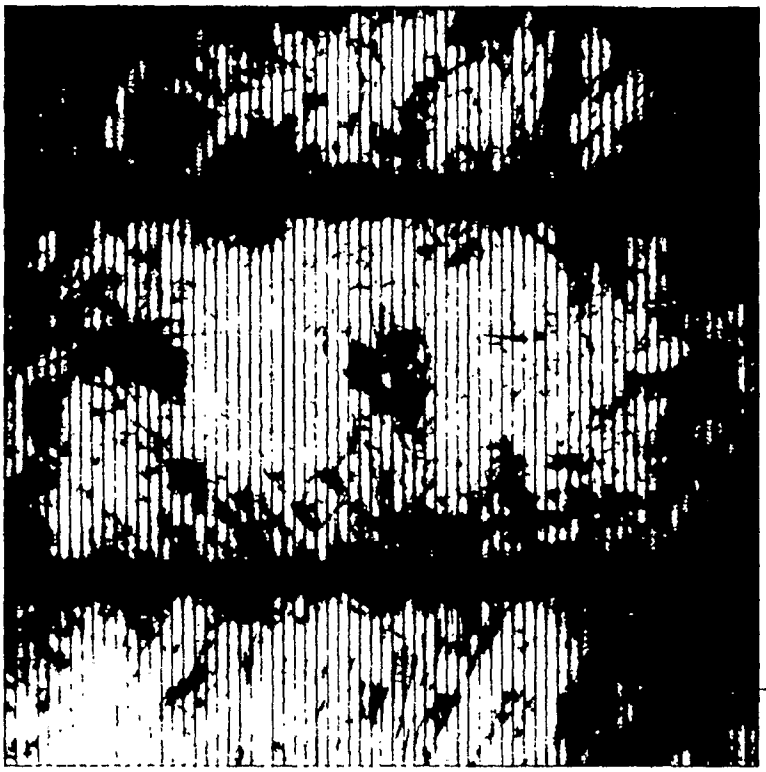

Fig. 5

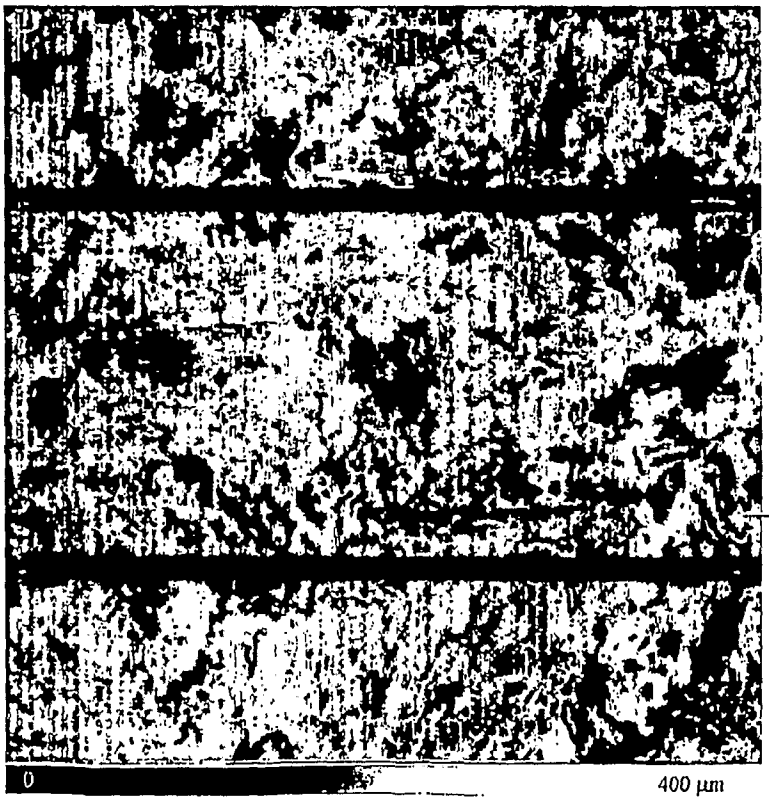

Fig. 6

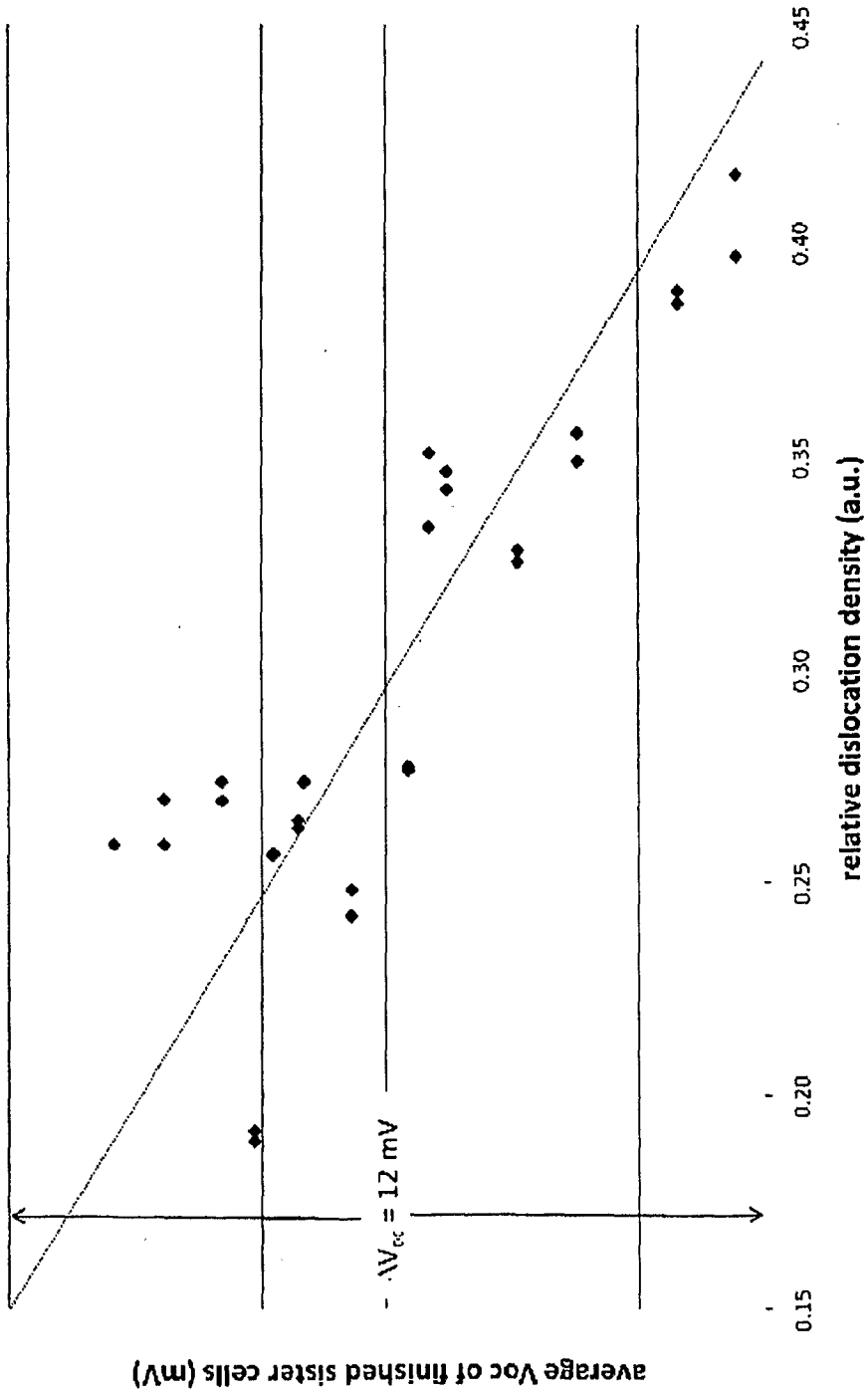
average Voc of finished sister cells (mV)
- ΔV_{oc} = 12 mV
0.15
0.20
0.25
0.30
0.35
0.40
0.45
relative dislocation density (a.u.)

Fig. 7

Fig. 8

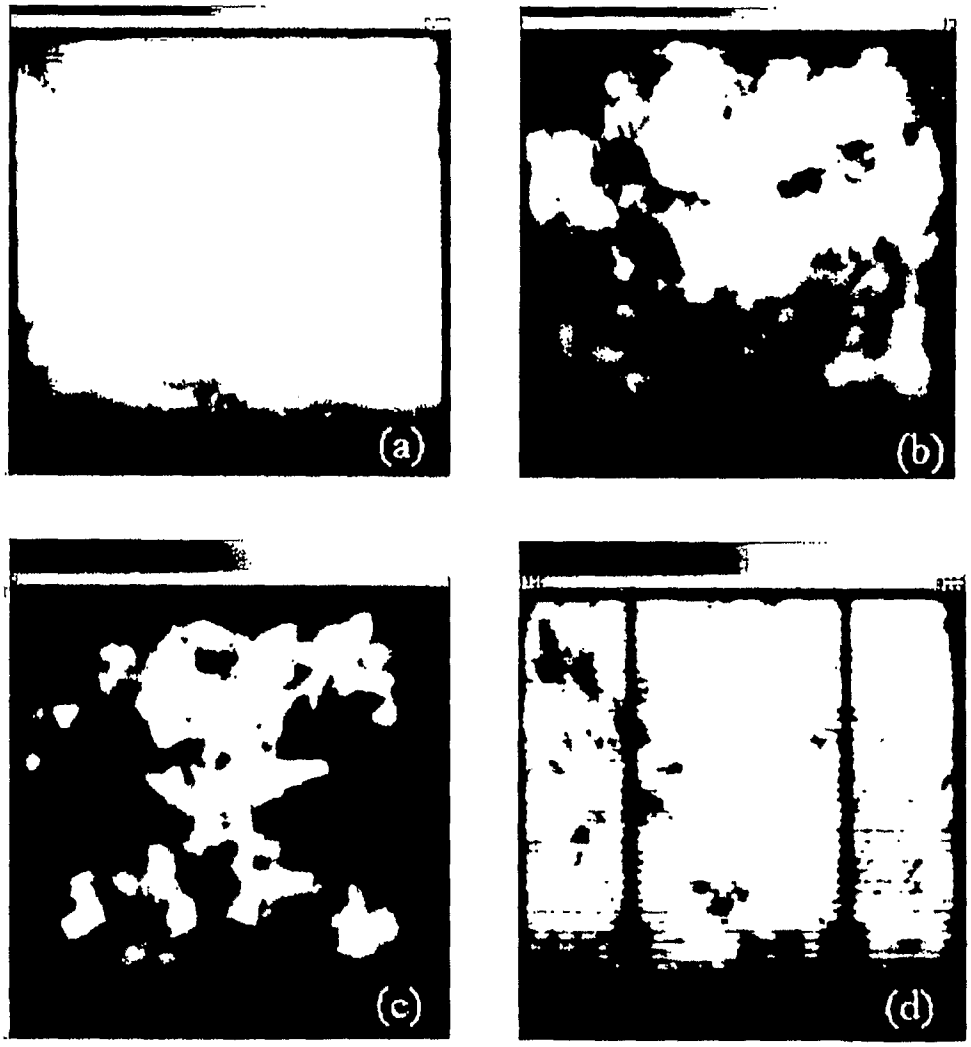

Fig. 9

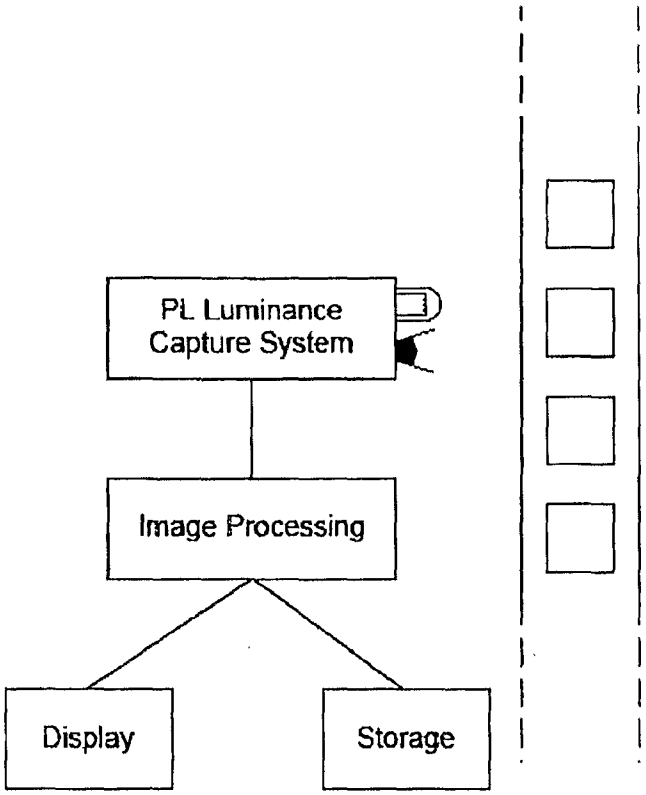
PL Luminance
Capture System
Image Processing
Display
Storage

Fig. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2009/000396

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

H01L 31/18 (2006.01) *G01N 21/66* (2006.01)

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
WPI, EPODOC, INSPEC, TXTUS1, TXTUS2, TXTUS3, TXTEP1, TXTGB1, TXTWO1, TXTAU1, TXTCA1, Patentscope, Google Scholar and keywords (bandgap?, defect, dislocat+, operat+ characteri+, predict+, correlat+, analy+, device, chip?, IC, class+, categori+, structur+, crystal+, photovoltaic, solar cell, and similar words)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2007/041758 A1 (NEWSOUTH INNOVATIONS PTY LIMITED) 19 April 2007 Abstract; page 5, lines 23–27; page 12, line 18, to page 14, line 2; page 19, lines 4–12;	3–25, 27, 30–31
Y	JP 2007-251004 A (TOYOTA CENTRAL RES & DEV LAB INC et al.) 27 September 2007, (Machine translation) retried from the internet 22 May 2009 <URL: http://aipn1.ipdl.inpit.go.jp/aipn_call_transl.ipdl?N0000=7200&N0120=01&N2001=2&N3001=H19-251004> Abstract; paragraphs 0017–0040, 0055–0056	3–25, 27, 30–31
Y	US 2006/0267007 A1 (SALZMAN et al.) 30 November 2006 Abstract; table I; paragraphs 0004–0012, 0039–0049 0061 and 0092	3–25, 27, 30–31
Y	JP 08-139196 (RICOH CO LTD) 31 May 1996 (machine translation) retrieved from the internet 22 May 2009, <URL: http://www4.ipdl.inpit.go.jp/Tokujitu/PAJdetail.ipdl?N0000=60&N0120=01&N2001=2&N3001=H08-139196> Abstract; figure 1; paragraphs 0002–0004	3–25, 27, 30–31

[X] Further documents are listed in the continuation of Box C [X] See patent family annex

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"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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 June 2009	19 JUN 2009
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. +61 2 6283 7999	Authorized officer **STEPHEN HARKER** AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No : +61 2 6283 7962

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2009/000396

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	Trupke et al., 'Photoluminescence imaging of silicon wafers', Applied Physics Letters, Vol. 89, pages 044107, 2006, downloaded from the internet, 29 May 2009, <URL: http://www.btimaging.com/Pdfs/I1%20PL%20Imaging%20APL%2089%20p044107%20(2006).pdf> Abstract; Figure 4; page 044107-3	21
A	Fuyuki et al., 'Photographic surveying of minority carrier diffusion length in polycrystalline silicon solar cells by electroluminescense', Applied Physics Letters, Vol. 86, pages 262108, 2005, downloaded from the internet , 2 June 2009, <URL: http://mswebs.naist.jp/LABs/fuyuki/ronbun-list/ronnbunnlist-image/IEEE1_paper_fuyuki.pdf>	
A	Siegelin et al., 'Dislocation related leakage in advanced CMOS devices', Proceedings of the 31st International Symposium for Testing and Failure Analysis, 6–10 November 2005, pages 59–63, ASM International, 2005, downloaded from the internet, 7 May 2009, <URL: http://www.multiprobe.com/technology/technologyassets/03_4_Dislocation_related_Leakage_in_Advanced_CMOS_devices.pdf>	
A	Niedernostheide et al., 'Analysis of radiation-induced defects and performance conditioning in high-power devices', Journal of the Electrochemical Society, Vol. 15, No. 1, pages G15–G21, 2003	
A	Liao et al., 'A comprehensive study of Indium implantation-induced damage in deep submicrometer nMOSFET: Device characterization and damage assessment', IEEE Transactions on Electron Devices, Vol. 49, No. 12, pages 2254–2262, December 2002	
	Note on the Y indications: WO 2007/041758 can be combined with any one of JP 2007-251004, US 2006/0267007 or JP 08-139196 with regard to claims 3–20, 22–25, 27, 30–31. An additional combination of the above with Trupke et al. covers claim 21.	

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2009/000396

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

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

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

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

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

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

This International Searching Authority found multiple inventions in this international application, as follows:
This International Application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept.

[See Supplemental Box]

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
After discussion with the applicant it was agreed that a single search fee would cover a search on the invention mentioned in the claims Nos.: 3–5, 6–25 (when appended to claims 3–5), 27 and 30–31

Remark on Protest

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

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

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2009/000396

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

Continuation of Box No: III

This International Application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept.

In assessing whether there is more than one invention claimed, I have given consideration to those features which can be considered to potentially distinguish the claimed combination of features from the prior art. Where different claims have different distinguishing features they define different inventions.

This International Searching Authority has found that there are different inventions as follows:

- Claims 1, claims 6–25 (when appended to claim 1), 26 and 28 are directed to methods and systems for analysing and classifying bandgap materials including silicon wafers using luminescence techniques to obtain information about defects.
- Claims 2 and 29 are directed to methods and systems for analysing and classifying bandgap materials including silicon wafers using any technique to obtain information about defects.
- Claims 3, claims 6–25 (when appended to claim 3), 27 and 30 are directed to methods and systems for correlating and predicting device characteristics of bandgap materials including silicon wafers on the basis of luminescence techniques to obtain information about defects.
- Claims 4, 5, claims 6–25 (when appended to claims 4 or 5) and 31 are directed to methods or systems for correlating and predicting device characteristics of bandgap materials including silicon wafers using any technique to obtain information about defects.
- Claims 32 and 33 are directed to methods and systems for distinguishing dislocation defects and grain boundaries in multicrystalline silicon wafers by comparing luminescence and optical images.
- Claims 34–39 are directed to monitoring/controlling processes for reducing the density of defects in bandgap materials by comparing luminescence images before and after the process.

PCT Rule 13.2, first sentence, states that unity of invention is only fulfilled when there is a technical relationship among the claimed inventions involving one or more of the same or corresponding special technical features. PCT Rule 13.2, second sentence, defines a special technical feature as a feature which makes a contribution over the prior art.

The only feature common to all of the claims is detecting and analysing defects in bandgap materials. However this concept is not novel in the light of:

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This means that the common feature can not constitute a special technical feature within the meaning of PCT Rule 13.2, second sentence, since it makes no contribution over the prior art.

Because the common feature does not satisfy the requirement for being a special technical feature it follows that it cannot provide the necessary technical relationship between the identified inventions. Therefore the claims do not satisfy the requirement of unity of invention *a posteriori*.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/AU2009/000396

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

Patent Document Cited in Search Report		Patent Family Member					
WO	2007041758	AU	2006301905	CN	101365937	EP	1946079
		KR	20080089566	US	2009051914		
JP	2007251004	NONE					
US	2006267007	US	2007018192				
JP	8139196	NONE					

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

END OF ANNEX