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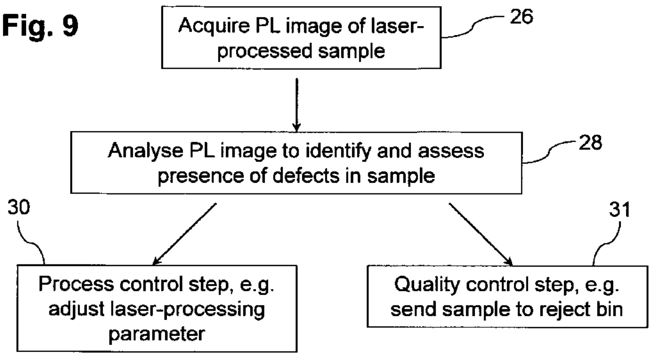
Fig. 9



(57) **Abstract**: Photoluminescence-based methods and systems are presented for monitoring laser processing steps in the manufacture of solar cells. The methods and systems can be used for process control purposes (e.g. adjusting a parameter of the laser exposure) or for quality control purposes (e.g. rejection of defective samples). In certain embodiments photoluminescence imaging is performed during or after a laser processing step to gauge the extent of defects induced by the laser exposure, while in other embodiments photoluminescence imaging is performed before a laser processing step to direct or adjust the subsequent laser exposure. The methods and systems of the invention can be used for example in an R&D environment to optimise a laser processing step, or in-line for real time process control or quality control of a laser processing step in a solar cell manufacture line. Laser processing in solar cell manufacture may for example be used for edge isolation or selective emitter formation.

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Control of Laser Processing Steps in Solar Cell Manufacture

Field of the Invention

The present invention relates to systems and methods for monitoring laser processing steps in the manufacture of solar cells, and in particular to the use of photoluminescence imaging for process control and quality control of such steps. However the invention is not limited to this particular field of use.

Background of the Invention

The following discussion of the prior art is provided to place the invention in an appropriate technical context and enable the advantages of it to be more fully understood. It should be appreciated, however, that any discussion of the prior art throughout the specification should not be considered as an express or implied admission that such prior art is widely known or forms part of common general knowledge in the field.

Many process steps in the manufacture of semiconductor solar cells, both wafer-based (e.g. multicrystalline or monocrystalline silicon cells) and thin film (e.g. amorphous silicon on glass), require the use of high intensity laser beams. For example a laser beam **1** can be used to etch a trench **2** through an emitter layer **4** of a silicon wafer **6** in an edge isolation process as shown in Figure 1, or through a thin amorphous silicon layer **8** on a glass substrate **10** as shown in Figure 2, for example to separate thin film solar cells. Certain high efficiency solar cell designs require holes **12** to be drilled through a wafer **6** for wrap through of an emitter layer **4** or metallization **14** as shown in Figures 3 and 4 respectively, while a laser can also be used to form local openings in a dielectric layer (e.g. silicon nitride or oxide) for improved back surface passivation. Lasers are also commonly used for spot isolation and for wafer marking and cutting.

Yet another application of lasers in solar cell manufacture is selective emitter formation and metallization. An emitter layer, e.g. an n^{++}-type layer on a p-type wafer formed for example by diffusing a suitable dopant (e.g. phosphorus for n-doping) into the surface, is typically required to transport charge carriers to and into the metal finger contacts. However the emitter layer also absorbs a significant proportion of the high energy (blue) portion of the solar spectrum, causing a reduction in cell efficiency of about 2% in absolute terms (e.g. from 17% to 15%). For high efficiency cells, it is therefore desirable to form an emitter layer in a selective fashion, lightly doped (for reduced blue absorption) in all areas except under the metal lines. Once the selective emitter has been formed, it is then necessary to form the metal lines on the highly doped regions. Both requirements can be satisfied by the 'laser doped selective emitter' (LDSE) process described in US Patent No 6,429,037 entitled 'Self Aligning Method for Forming a Selective Emitter and Metallization in a Solar Cell'. Briefly, this process comprises the steps of: coating the front surface of a silicon wafer **6** with one or more dielectric layers **16** that serve as a diffusion source for the emitter layer and as a metallization mask (Figure 5); heating the wafer to form a lightly doped emitter layer **4** (Figure 6); exposing the wafer to a laser beam **1** to melt a localised portion of the silicon and the overlying dielectric layer to produce one or more regions **20** with a higher doping density than the surrounding emitter layer **4** (Figure 7); and finally a self-aligned metallization step where metal contacts **22** are produced, e.g. by electroplating, on top of the highly-doped regions (Figure 8). The self-alignment occurs by virtue of the dielectric layer **16** doubling as a metallization mask, with metallization occurring only in those regions where the dielectric layer has been disrupted by the laser.

It will be appreciated that most if not all of the above-mentioned processing steps involve the ablation or melting of material, necessitating high intensity laser beams, e.g. from Nd:YAG lasers (1064 nm) or frequency-doubled Nd:YAG lasers (532 nm) operating in continuous wave or pulsed mode. These processing steps have a number of complications that can compromise cell efficiency. For example the localised heating from the laser beam causes thermal stress in the surrounding silicon, possibly leading to dislocations that reduce carrier lifetime or cracks that interrupt current flow and potentially grow to cause catastrophic cell failure. The heating can also volatilise hydrogen in passivated samples, resulting in de-passivation of carrier recombination sites such as surfaces, grain boundaries and point defects, and furthermore the hydrogen can migrate to the boundary of the molten silicon causing micro channels that, after metallization, can result in shunts. Insufficient laser exposure can also cause problems such as incomplete edge isolation or, in the LDSE process, incomplete mixing of the molten silicon and the emitter dopant resulting in a mixed phase with a high concentration of recombination sites. Although these problems can be ameliorated individually, they are on occasion counter-optimised. For example the shunting problem can be reduced by driving hydrogen off locally with an initial low power laser beam pass, but this contributes to the de-passivation problem.

Problems can also occur if a laser processing step is performed on a less than ideal portion of a sample. For example it would be better for cell efficiency if a selective emitter/metallization section avoided a region with a high concentration of dislocations or impurities, while laser processing of an area with an inclusion (e.g. silicon carbide crystal in a silicon wafer) may be more likely to cause cracking.

There is a need therefore for a technique to inspect a semiconductor wafer or thin film material before, during and/or after a laser processing step. Ideally, the technique should be sufficiently fast to be used in-line to inspect all or a significant fraction of the precursor cells passing through a laser processing station.

Summary of the Invention

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 systems and methods for inspecting selected semiconductor samples before, during and/or after a laser processing step. It is another object of the present invention in its preferred form to provide systems and methods for in-line inspection of semiconductor samples passing through a laser processing station.

According to a first aspect the present invention provides a method for processing a semiconductor sample, said method comprising the steps of:

(a) after performing a laser processing step on a region of said semiconductor sample, illuminating at least said region with a predetermined illumination to produce photoluminescence from said sample in response to said illumination;

(b) acquiring an image of the photoluminescence emitted from said sample; and

(c) processing said image to obtain information on defects present in said sample after said laser processing step.

Preferably the method further comprises the step of (d) adjusting a parameter of the laser processing step based on the information. The parameter preferably comprises laser power, pulse repetition rate and/or scanning rate.

Preferably the method further comprises the step of (e) adjusting the position or orientation of the sample relative to a subsequent processing station based on the information.

Preferably the method further comprises the step of (f) determining a destination of the sample based on the information. The destination preferably comprises a reject bin, a high quality cell line, a standard quality cell line, or a remediation line.

According to a second aspect the present invention provides a method for processing a semiconductor sample, said method comprising the steps of:

(a) prior to performing a laser processing step on a region of said semiconductor sample, illuminating at least said region with a predetermined illumination to produce photoluminescence from said sample in response to said illumination;

(b) acquiring an image of the photoluminescence emitted from said sample;

(c) processing said image to obtain information on defects present in said sample prior to said laser processing step; and based on said information,

(d) performing said laser processing step, or

(e) redirecting said sample to a reject bin or a remediation line.

Preferably the method further comprises the step of (f) adjusting a parameter of the laser processing step based on the information. The parameter preferably comprises laser power, pulse repetition rate and/or scanning rate.

Preferably the method further comprises the step of (g) adjusting the position or orientation of the sample relative to an apparatus used to perform the laser processing step based on the information.

The defects may comprise dislocations, cracks, micro-channels, impurity-rich areas, shunts and/or areas of reduced minority carrier lifetime. The semiconductor sample may comprise a multicrystalline silicon wafer, a monocrystalline silicon wafer, or a thin film comprising amorphous silicon, crystalline silicon, an amorphous silicon-germanium alloy, a crystalline silicon-germanium alloy, crystalline germanium, cadmium telluride, CIGS, or a III-V semiconductor based on gallium, aluminium and/or indium arsenide.

Preferably the laser processing step occurs during a stage in the manufacture of a solar cell, said stage comprising edge isolation, spot isolation, cell isolation, selective emitter formation, emitter wrap through, metallization wrap through, back surface passivation, laser marking or laser cutting.

According to a third aspect the present invention provides a method for processing a semiconductor sample, said method comprising the steps of:

(a) acquiring a first photoluminescence image of said sample prior to performing a laser processing step on said sample;

(b) processing said first image to obtain pre-exposure information on defects present in said sample prior to performing said laser processing step;

(c) performing said laser processing step on said sample;

(d) acquiring a second photoluminescence image of said sample after performing said laser processing step;

(e) processing said second image to obtain post-exposure information on defects present in said sample after performing said laser processing step; and

(f) comparing said post-exposure information with said pre-exposure information to obtain data on defects induced in said sample by said laser processing step.

Preferably the data comprises the quantity, type and/or location of defects induced in the sample.

Preferably the method further comprises the step of (g) adjusting a parameter of the laser processing step based on the data. The parameter preferably comprises laser power, pulse repetition rate and/or scanning rate.

Preferably the method further comprises the step of (h) determining a destination of the sample based on the data. The destination preferably comprises a reject bin, a high quality cell line, a standard quality cell line, or a remediation line.

According to a fourth aspect the present invention provides a method for processing a semiconductor sample, said method comprising the steps of:

(a) while performing a laser processing step on a region of said semiconductor sample, illuminating at least said region with a predetermined illumination to produce photoluminescence from said sample in response to said illumination;

(b) acquiring at least one image of the photoluminescence emitted from said sample; and

(c) processing said at least one image to obtain information on defects in said sample.

Preferably step (c) comprises obtaining information on defects present in the sample before the laser processing step and/or defects being induced in the sample by the laser processing step.

Preferably the method further comprises the step of (d) adjusting a parameter of the laser processing step based on the information. The parameter preferably comprises laser power, pulse repetition rate and/or scanning rate.

Preferably the method further comprises the step of (e) determining, based on the information, a destination of the sample after completion of the laser processing step. The destination preferably comprises a reject bin, a high quality cell line, a standard quality cell line, or a remediation line.

Preferably the methods of the invention are performed in-line on a solar cell manufacturing line.

According to a fifth aspect the present invention provides a system for processing a semiconductor sample, said system comprising a photoluminescence imaging apparatus and a laser processing station, wherein said photoluminescence imaging apparatus comprises:

an illumination source for illuminating said sample with a predetermined illumination to produce photoluminescence from said sample in response to said illumination;

an image acquisition device for acquiring at least one image of the photoluminescence emitted from said sample; and a processor for processing said at least one image to obtain information on defects present in said sample or induced in said sample in a laser processing step;

and wherein said laser processing station comprises:

a laser for performing a laser processing step on said sample; and

a controller for controlling said laser.

Preferably the photoluminescence imaging apparatus and the laser processing station are housed within a common laser safety enclosure. Preferably the controller is configured to adjust a parameter of the laser in response to the information on defects present or induced in the sample.

Preferably the system further comprises:

a transport mechanism for transporting the sample from the photoluminescence imaging apparatus to the laser processing station; and

a sample handling mechanism provided between the photoluminescence imaging apparatus and the laser processing station.

In one embodiment the sample handling mechanism is configured to direct the sample to a reject bin in response to the information on defects present or induced in the sample.

In another embodiment the sample handling mechanism is configured to direct the sample to a remediation line in response to the information on defects present or induced in the sample.

In a further embodiment the sample handling mechanism is configured to direct the sample to an alternate process line in response to the information on defects present or induced in the sample.

In yet another embodiment the sample handling mechanism is configured to adjust the position or orientation of the sample relative to the laser processing station in response to the information on defects present or induced in the sample.

Alternatively the system further comprises:

a transport mechanism for transporting the sample from the laser processing station to the photoluminescence imaging apparatus; and

a sample handling mechanism provided after the photoluminescence imaging apparatus.

In one embodiment the sample handling mechanism is configured to direct the sample to a reject bin in response to the information on defects present or induced in the sample.

In another embodiment the sample handling mechanism is configured to direct the sample to a remediation line in response to the information on defects present or induced in the sample.

In a further embodiment the sample handling mechanism is configured to direct the sample to an alternate process line in response to the information on defects present or induced in the sample.

Preferably the photoluminescence imaging apparatus and the laser processing station are co-located.

In other embodiments the system further comprises a sample handling mechanism for directing the semiconductor sample to a destination after the sample exits the photoluminescence imaging apparatus and the laser processing station.

In one embodiment the sample handling mechanism is configured to direct the sample to a reject bin in response to the information on defects present or induced in the sample.

In another embodiment the sample handling mechanism is configured to direct the sample to a remediation line in response to the information on defects present or induced in the sample.

In a further embodiment the sample handling mechanism is configured to direct the sample to an alternate process line in response to the information on defects present or induced in the sample.

In certain embodiments the system further comprises a sample handling mechanism configured to adjust the position or orientation of the sample relative to a subsequent processing station in response to the information on defects present or induced in the sample.

Preferably a single optical source serves as the illumination source and as the laser.

According to a sixth aspect the present invention provides a system when used to implement the method according to any one of the first to fifth aspects.

According to a seventh aspect the present invention provides a semiconductor sample when processed by the method according to any one of the first to fourth aspects, or by the system according to the fifth aspect.

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’.

In describing and claiming the present invention, it is to be understood that the terminology used herein is for the purpose of describing particular embodiments of the invention only and is not intended to be limiting. Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood by one having ordinary skill in the art to which the invention pertains.

Brief Description of the Drawings

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 shows in side view a laser edge isolation process;

Fig. 2 shows in side view the laser scribing of a trench through a thin semiconductor layer on glass;

Fig. 3 shows in side view a section of a solar cell with a wrap through emitter layer;

Fig. 4 shows in side view a section of a solar cell with a wrap through metallization path;

Fig. 5 shows in side view a phosphorus-containing dielectric layer on the surface of a boron-doped silicon wafer;

Fig. 6 shows the formation of a lightly doped emitter layer on the silicon surface by thermal treatment of the dielectric layer shown in Fig. 5;

Fig. 7 shows the selective formation of a highly doped emitter region by laser exposure of the lightly doped emitter layer shown in Fig. 6;

Fig. 8 shows a conductor track formed by metallization of the highly doped emitter region shown in Fig. 7;

Fig. 9 shows a flowchart illustrating 'post-exposure' process monitoring methods according to certain embodiments of the invention;

Fig. 10 shows a flowchart illustrating 'pre-exposure' process monitoring methods according to certain embodiments of the invention;

Fig. 11 shows a flowchart illustrating process monitoring methods according to certain embodiments of the invention;

Fig. 12 shows in side view a system for monitoring a laser processing step in a solar cell manufacture line;

Fig. 13 shows a system for monitoring a laser processing step in a solar cell manufacture line according to a preferred embodiment of the invention; and

Fig. 14 shows a system for monitoring a laser processing step in a solar cell manufacture line according to another preferred embodiment of the invention.

Detailed Description

Preferred embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings.

Photoluminescence (PL) imaging is known to be a rapid and convenient technique for characterising semiconductor samples such as silicon bricks, wafers and thin films, and in particular silicon-based solar cells both during and after manufacture. As discussed in T. Trupke *et al* 'Progress with Luminescence Imaging for the Characterisation of Silicon Wafers and Solar Cells', 22nd European Photovoltaic Solar Energy Conference, Milan, September 2007, the PL emission from silicon samples can provide information on many material and electrical parameters of relevance to solar cell performance, including minority carrier diffusion length, minority carrier lifetime, series resistance, shunts, impurities, dislocations and cracks. The PL emission from silicon arises primarily from band-to-band recombination, in the wavelength range 900 to 1300 nm, although emission at longer wavelengths can also occur from defects such as dislocations. Suitable apparatus and methods for performing PL imaging of silicon and other semiconductor materials are described in PCT Publication No WO 2007/041758 A1 entitled ‘Method and System for Inspecting Indirect Bandgap Semiconductor Structure’ and incorporated herein by reference.

PL imaging of a semiconductor sample typically involves exposing a surface of the sample to an illumination chosen to produce PL (typically above band-gap light for generating band-to-band PL), acquiring or capturing an image of the PL emitted from the sample in response to the illumination, and processing the image to highlight or obtain a measure of one or more features of interest. A description of the imaging process may on occasion omit the illumination or optical excitation step, but it will be implicitly present in the acquisition or capture of a PL image. Luminescence generated from a combination of optical and electrical excitation, e.g. current injection or extraction at the terminals of a solar cell, discussed for example in PCT Publication No WO 2007/128060 A1 entitled ‘Method and System for Testing Indirect Bandgap Semiconductor Devices Using Luminescence Imaging’ and incorporated herein by reference, is also considered to be photoluminescence for the purposes of this specification.

As discussed in the Background section, lasers can be used in a number of process stages in solar cell manufacture. There are several aspects of PL imaging that make it suitable for monitoring a laser-based processing step. Firstly, the PL signal emitted from silicon is known to be sensitive to the presence of most if not all of the types of defects likely to be caused by the laser exposure. For example dislocations act as minority carrier recombination sites, and appear as ‘dark’ areas in a PL image because the locally enhanced non-radiative recombination rate, equivalent to a locally reduced carrier lifetime, reduces the concentration of carriers available for radiative recombination.

Specific techniques relating to the measurement of minority carrier lifetime (or diffusion length) and dislocation densities are described in PCT Publication Nos WO 2008/014537 A1 and WO 2009/121133 A1 respectively. Similarly, de-passivation caused by hydrogen volatilisation is likely to result in a local reduction in carrier lifetime, as will micro-channels caused by hydrogen accumulation. Shunted regions in solar cells can also be detected by PL imaging, as disclosed for example in O. Breitenstein *et al* 'On the Detection of Shunts in Silicon Solar Cells by Photo- and Electroluminescence Imaging', Prog. Photovolt: Res. Appl. **16**:325-330 (2008) and M. Kasemann *et al* 'Luminescence Imaging for the Detection of Shunts on Silicon Solar Cells', Prog. Photovolt: Res. Appl. **16**:297-305 (2008). Furthermore as disclosed in PCT Publication No WO 2010/019992 A1, PL measurements can also be useful for detecting *potential* shunts, i.e. in partially processed cells before metallization. It should be noted that shunts and potential shunts can also be detected globally by their influence on the overall PL signal from a sample. PL imaging also has the ability to detect cracks in solar cells or solar cell precursors, as described for example in PCT Publication Nos WO 2009/026661 A1 and WO 2011/017772 A1.

A high concentration of recombination sites resulting from incomplete mixing of the molten silicon and the emitter dopant because of insufficient laser exposure in an LDSE process will be detectable from a local reduction in PL signal, for reasons explained above. Incomplete mixing may also result in a high local series resistance, detectable by methods disclosed in PCT Publication Nos WO 2007/128060 A1 and WO 2009/129575 A1.

In a first aspect of the invention, methods are presented for monitoring a laser processing step in a solar cell manufacture line. In certain embodiments of the invention, PL imaging is used to monitor a laser processing step by inspecting samples after the laser exposure, looking for any of the above-described defects that may have been induced by the exposure. In certain embodiments this 'post-exposure' inspection is used for process control purposes. As shown in Figure 9, a PL image of a laser-processed sample is acquired in a PL imaging step **26** and analysed in an image processing step **28** to identify and assess the presence of defects in the sample. This image processing step may for example comprise electronic filtering, line detection algorithms or deconvolution with point spread functions that can reveal features such as dislocations and cracks more clearly. Finally, in a process control step **30** a parameter of the laser processing step such as laser power, pulse rate or scan speed is adjusted if required. While there is a possibility that a given defect (e.g. a crack or a low lifetime region) in a given sample may have been pre-existing, the presence of such a defect in repeated samples is a more certain indicator of a problem with the laser exposure. Alternatively the process control step can comprise adjusting the position or orientation of the sample relative to a subsequent processing station in a solar cell manufacture line. In other embodiments the 'post-exposure' inspection is used for quality control purposes. Referring again to Figure 9, after the presence of any defects in a sample has been determined in the image processing step **28**, a quality determination of the sample followed by some action is performed in a quality control step **31**. For example severely defective samples can be transported to a reject bin to avoid wasting further resources on them, while other samples can be sent to high efficiency cell lines, standard cell lines or remediation lines depending on the quality assessment. A remediation line may for example be used to ameliorate defects induced by the laser processing step. The process control step **30** and the quality control step **31** may be viewed as alternatives, although in other embodiments both are implemented.

While it is envisaged that most deleterious effects of the LDSE process will occur as a result of the laser exposure as shown in Figure 7, it is also possible that the subsequent metallization step (Figure 8) could have an adverse effect on the sample properties, for example by completing a shunt. Therefore in certain embodiments PL measurements (either spatially-resolved images or global measurements as described in PCT Publication No WO 2010/019992 A1) are performed after the metallization step, either additionally or alternatively to image acquisition after the laser doping step. After metallization, luminescence can also be generated by electrical excitation if required, by connecting the contact terminals to a voltage source.

Several defects including cracks, dislocations, inclusions and impurities could be present in the samples entering a laser processing station, having been present in the initial feedstock or induced by an earlier processing step. In certain embodiments of the invention, PL imaging is used to monitor a laser processing step by inspecting samples before the laser exposure, looking for defects that may compromise the outcomes of this step. In certain embodiments this 'pre-exposure' inspection is used for process control purposes. As shown in Figure 10, a PL image of a sample prior to laser-processing is acquired in a PL imaging step **32** and analysed in an image processing step **28** to identify the presence of defects in the sample. Finally, in a process control step **30** a parameter of the laser processing step such as laser power, pulse rate or scan speed is adjusted if required for example to mitigate the risk of an adverse effect such as crack propagation. Alternatively the process control step can comprise adjusting the position or orientation of the sample relative to the laser processing station, e.g. by turning or moving the sample or moving the laser beam, to avoid a defect-rich or impurity-rich region or a micro-crack. In other embodiments the 'pre-exposure' inspection is used for quality control purposes. Referring again to Figure 10, after the occurrence of any defects in a sample has been determined in the image processing step **28**, a quality determination of the sample followed by some action is performed in a quality control step **31**. For example severely defective samples can be shunted off into a reject bin, high quality samples can continue on to the laser processing step (e.g. for selective emitter formation) while lower quality samples can be sent to a standard cell line or a remediation line depending on the quality assessment. The process control step **30** and the quality control step **31** may be viewed as alternatives, although in other embodiments both are implemented.

In yet other embodiments of the invention, PL imaging is used to monitor a laser processing step by inspecting samples both before and after the laser exposure, for example to provide more certainty that a given defect was actually caused by the laser exposure or to determine whether the laser exposure enlarged a micro-crack. Again, this inspection process can be used for quality control or process control purposes.

In further embodiments of the invention, PL imaging is used to monitor a laser processing step by inspecting samples during the laser exposure, looking for defects induced by the laser. In certain embodiments this inspection is used for process control purposes. As shown in Figure 11, one or more PL images of a sample are acquired during laser-processing in a PL imaging step **35** and analysed in an image processing step **28** to identify and assess the presence of defects induced in the sample. Finally, in a process control step **30** a parameter of the laser processing step such as laser power, pulse rate or scan speed is adjusted if required, e.g. to reduce the rate of defect formation. By acquiring and processing several PL images during a given laser processing step, it may be possible to identify a problem as soon as it occurs and adjust the process conditions accordingly. In other embodiments the inspection is used for quality control purposes. Referring again to Figure 11, after the occurrence of any defects in a sample has been determined in the image processing step **28**, a quality determination of the sample followed by some action is performed in a quality control step **31**. For example depending on the quality assessment samples can be directed to a reject bin, a remediation line, a high quality cell line or a standard quality cell line. The process control step **30** and the quality control step **31** may be viewed as alternatives, although in other embodiments both are implemented.

Performing PL imaging during a laser processing step may require some care, particularly if the laser wavelength is sufficiently short (i.e. above the band gap of the semiconductor material) to induce photoluminescence. For example a frequency-doubled Nd:YAG laser (532 nm) could induce photoluminescence from silicon, which has a band gap of approximately 1.1 eV (~1125 nm), whereas a CO_2 laser (10.6 μm) could not. This potential problem can be avoided by acquiring PL images when the laser beam is off, e.g. between pulses or while the laser is being moved to another portion of the sample. It will be appreciated therefore that the acquisition of PL images 'during' a laser processing step does not necessarily mean that the PL images are acquired while the laser beam is actually interacting with the sample, although this may be the case. It may also be advantageous for the PL emission to be collected from the back surface of the sample, so that the sample itself helps to shield the detector from the laser light. In any event it should be relatively simple to prevent laser light entering the camera by means of appropriate filters, and in many cases the long pass filter commonly used in PL imaging to prevent the excitation light entering the camera will suffice.

PL images of silicon samples can be acquired and processed on a timescale of fractions of a second to 2 seconds, especially for the post-passivation samples that will usually be encountered at a laser-processing stage of a solar cell line such as edge isolation or selective emitter formation. This is because passivation significantly increases the radiative quantum efficiency, and hence the PL signal, of silicon wafers. This timescale is fast enough for in-line characterisation of samples on silicon solar cell manufacturing lines that currently operate with a throughput of order 1 wafer per second. Accordingly, in certain embodiments of the invention measurements are performed in an 'in-line' manner where PL images are acquired from all or a significant fraction of the samples before or after laser processing. In yet other embodiments PL images can be acquired during the laser processing.

In other embodiments of the invention measurements are performed in an 'off-line' manner, applicable for example to optimising the laser processing conditions or examining failure modes for process development purposes before the laser processing station is introduced into a solar cell manufacturing line, or to process monitoring/quality control purposes where selected samples are removed from a solar cell manufacturing line. The measurement time available in these situations is obviously much greater than in an in-line situation, enabling the use of a greater number of PL measurement and image processing techniques. For example quantitative series resistance imaging can take of order 30 seconds or longer depending on the desired spatial resolution and accuracy among other factors. Other lasers could also be trialled to determine whether the precise wavelength or operating mode (e.g. pulsed versus continuous wave) has a significant effect on the laser processing and possible side effects.

In a second aspect of the invention, systems are presented for monitoring a laser processing step in a solar cell manufacture line. In certain embodiments of the invention a system **33** comprises a combination of a laser processing station **34** and a PL imaging apparatus **36** as shown in Figure 12. Suitable PL imaging apparatus are described in the above-mentioned PCT Publication No WO 2007/041758 A1, and typically comprise an excitation module **38** comprising an illumination source, a short pass filter and collimating optics, an imaging module **40** comprising focussing optics, a long pass filter and a suitable camera, and an image processor **42** for processing the PL images. A typical laser processing station comprises a laser **44** and a controller **46** for controlling the power, pulse rate (if applicable) and direction of the laser beam among other parameters.

In embodiments suitable for in-line applications the system **33** further comprises a transport mechanism **48** such as a transport belt for transporting a sample **50** between the laser processing station and the PL imaging apparatus, and a sample handling mechanism **52** for moving or turning a sample or for directing samples to a reject bin or another process line. In certain embodiments the transport mechanism operates in the direction indicated by the arrow **54** such that a sample is inspected by the PL imaging apparatus before the laser processing, while in other embodiments the transport mechanism operates in the direction indicated by the arrow **56** such that a sample is inspected by the PL imaging apparatus after laser processing. In yet other embodiments a PL imaging apparatus is provided before and after the laser processing station. In preferred embodiments the PL imaging apparatus and the laser processing station are co-located so that PL images can be acquired before, during or after a laser processing step as required, potentially improving processing speed by removing the requirement to transport a sample between separate laser processing and PL imaging stations. For off-line applications where samples can be handled manually, automated transport and sample handling mechanisms may not be required.

PL imaging of silicon or other indirect bandgap semiconductors generally requires relatively high intensity illumination sources, frequently but not necessarily lasers. The light safety requirements for the laser processing station are therefore unlikely to be less stringent than those for the PL imaging apparatus, reducing the amount of engineering required to combine a PL imaging apparatus with a laser processing station. In preferred embodiments of the invention, a system **33** comprising a laser processing station **34** and a PL imaging apparatus **36** is provided in a common laser safety enclosure **58** as shown in Figure 13. It will be appreciated that the enclosure will have manual or automatic doors or shutters to allow insertion or removal of samples. The provision of a common laser safety enclosure is a further advantage of having co-located laser processing and PL imaging stations. As discussed previously it may be advantageous to acquire the PL images from the other side of the sample to the laser, using for example a configuration shown in Figure 14 where the PL imaging apparatus **36** and laser processing station **34** are on opposite sides of the sample **50**, inside a common laser safety enclosure **58**.

In certain embodiments a substantial area of a sample is illuminated in a single illumination step with light suitable for exciting photoluminescence from the sample, and a PL image of the area acquired in a single exposure with an area camera such as a silicon CCD camera. These embodiments often apply to stationary samples, for example in an off-line situation or on a process line modified to allow samples to be stopped for inspection, although the sample need not be stationary if the illumination is provided by a high intensity pulsed source such as a flash lamp. In alternative embodiments a sample area can be illuminated in line-scanning fashion, i.e. line-by-line with a linear light source, say as a sample moves along a process line, and a PL image acquired line-by-line with a line camera. Note that since any linear light source has a finite width, an illuminated line is considered to be an illuminated area. A PL image can also be acquired in point-wise fashion with a small area excitation beam (e.g. a focused laser beam) scanned across the sample surface, in which case a simple photo-detector can be used to detect the PL emission from each point; we refer to this situation as 'PL mapping' rather than PL imaging. Generally speaking, broad area illumination allows PL images to be acquired more rapidly, while small area (high intensity) illumination generates a stronger PL signal. Line-scanning configurations are particularly suitable for in-line applications.

If the laser used for the laser processing step is of a suitable wavelength and intensity for generating PL from the sample, it may be possible to use a single laser for both purposes, i.e. the laser processing station and the PL imaging apparatus could share a laser source. To this end it may be advantageous to have two interchangeable sets of optics for the laser, one to provide a focused beam for the laser processing and one to provide a broad area or line illumination for the PL imaging.

The invention has been described in terms of silicon wafer-based solar cells, but is not so limited. It could for example be applicable to other silicon-based devices or solar cells or other devices based on other indirect bandgap semiconductors such as germanium or silicon-germanium alloys or on direct bandgap semiconductors such as GaAs. Thin film solar cells based on a variety of semiconductor materials are also known, including amorphous silicon, crystalline silicon, amorphous silicon-germanium alloys, crystalline silicon-germanium alloys, crystalline germanium, cadmium telluride, $Cu(In,Ga)Se_2$

(CIGS), or III-V semiconductors based on gallium, aluminium and/or indium arsenide. In the manufacture of thin film solar cells lasers are used for cell separation, edge ablation, substrate cutting, marking sample identification, structuring the semiconductor and metal layers, and isolating poor areas of performance to reduce their impact on module efficiency, amongst other uses. Each of these processes can adversely affect the thin film solar cell via damage to the semiconductor, the substrate (often glass), the metal layers, or other layers. In addition, features detected by PL imaging prior to laser processing, during laser processing or after interactions with the laser in laser processing can lead to further site specific issues. In the case of thin films we note that PL imaging before, after or during laser processing, or some combination thereof, can lead to both quality control and process control actions.

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.

Claims:

1. A method for processing a semiconductor sample, said method comprising the steps of:
   (a) after performing a laser processing step on a region of said semiconductor sample, illuminating at least said region with a predetermined illumination to produce photoluminescence from said sample in response to said illumination;
   (b) acquiring an image of the photoluminescence emitted from said sample; and
   (c) processing said image to obtain information on defects present in said sample after said laser processing step.
2. A method according to claim 1, further comprising the step of (d) adjusting a parameter of said laser processing step based on said information.
3. A method according to claim 2, wherein said parameter comprises laser power, pulse repetition rate and/or scanning rate.
4. A method according to any one of the previous claims, further comprising the step of (e) adjusting the position or orientation of said sample relative to a subsequent processing station based on said information.
5. A method according to any one of the preceding claims, further comprising the step of (f) determining a destination of said sample based on said information.
6. A method according to claim 5, wherein said destination comprises a reject bin, a high quality cell line, a standard quality cell line, or a remediation line.
7. A method according to any one of the preceding claims, wherein said defects comprise dislocations, cracks, micro-channels, shunts and/or areas of reduced minority carrier lifetime.
8. A method according to any one of the preceding claims, wherein said semiconductor sample comprises a multicrystalline silicon wafer, a monocrystalline silicon wafer, or a thin film comprising amorphous silicon,

crystalline silicon, an amorphous silicon-germanium alloy, a crystalline silicon-germanium alloy, crystalline germanium, cadmium telluride, CIGS, or a III-V semiconductor based on gallium, aluminium and/or indium arsenide.

9. A method according to any one of the preceding claims, wherein said laser processing step occurs during a stage in the manufacture of a solar cell, said stage comprising edge isolation, spot isolation, cell isolation, selective emitter formation, emitter wrap through, metallization wrap through, back surface passivation, laser marking or laser cutting.

10. A method according to claim 9, when performed in-line on a solar cell manufacturing line.

11. A method for processing a semiconductor sample, said method comprising the steps of:

    (a) prior to performing a laser processing step on a region of said semiconductor sample, illuminating at least said region with a predetermined illumination to produce photoluminescence from said sample in response to said illumination;

    (b) acquiring an image of the photoluminescence emitted from said sample;

    (c) processing said image to obtain information on defects present in said sample prior to said laser processing step; and based on said information,

    (d) performing said laser processing step, or

    (e) redirecting said sample to a reject bin or a remediation line.

12. A method according to claim 11, further comprising the step of (f) adjusting a parameter of said laser processing step based on said information.

13. A method according to claim 12, wherein said parameter comprises laser power, pulse repetition rate and/or scanning rate.

14. A method according to any one of claims 11 to 13, further comprising the step of (g) adjusting the position or orientation of said sample relative to an apparatus used to perform said laser processing step based on said information.

15. A method according to any one of claims 11 to 14, wherein said defects comprise dislocations, cracks, impurity-rich areas, shunts and/or areas of reduced minority carrier lifetime.

16. A method according to any one of claims 11 to 15, wherein said semiconductor sample comprises a multicrystalline silicon wafer, a monocrystalline silicon wafer, or a thin film comprising amorphous silicon, crystalline silicon, an amorphous silicon-germanium alloy, a crystalline silicon-germanium alloy, crystalline germanium, cadmium telluride, CIGS, or a III-V semiconductor based on gallium, aluminium and/or indium arsenide.

17. A method according to any one of claims 11 to 16, wherein said laser processing step occurs during a stage in the manufacture of a solar cell, said stage comprising edge isolation, spot isolation, cell isolation, selective emitter formation, emitter wrap through, metallization wrap through, back surface passivation, laser marking or laser cutting.

18. A method for processing a semiconductor sample, said method comprising the steps of:

    (a) acquiring a first photoluminescence image of said sample prior to performing a laser processing step on said sample;

    (b) processing said first image to obtain pre-exposure information on defects present in said sample prior to performing said laser processing step;

    (c) performing said laser processing step on said sample;

    (d) acquiring a second photoluminescence image of said sample after performing said laser processing step;

    (e) processing said second image to obtain post-exposure information on defects present in said sample after performing said laser processing step; and

    (f) comparing said post-exposure information with said pre-exposure information to obtain data on defects induced in said sample by said laser processing step.

19. A method according to claim 18, wherein said data comprises the quantity, type and/or location of defects induced in said sample.

20. A method according to claim 18 or claim 19, further comprising the step of (g) adjusting a parameter of said laser processing step based on said data.

21. A method according to claim 20, wherein said parameter comprises laser power, pulse repetition rate or scanning rate.

22. A method according to any one of claims 18 to 21, further comprising the step of (h) determining a destination of said sample based on said data.

23. A method according to claim 22, wherein said destination comprises a reject bin, a high quality cell line, a standard quality cell line, or a remediation line.

24. A method according to any one of claims 18 to 23, wherein said defects comprise dislocations, cracks, micro-channels, impurity-rich areas, shunts or areas of reduced minority carrier lifetime.

25. A method according to any one of claims 18 to 24, wherein said semiconductor sample comprises a multicrystalline silicon wafer, a monocrystalline silicon wafer, or a thin film comprising amorphous silicon, crystalline silicon, an amorphous silicon-germanium alloy, a crystalline silicon-germanium alloy, crystalline germanium, cadmium telluride, CIGS, or a III-V semiconductor based on gallium, aluminium and/or indium arsenide.

26. A method according to any one of claims 18 to 25, wherein said laser processing step occurs during a stage in the manufacture of a solar cell, said stage comprising edge isolation, spot isolation, cell isolation, selective emitter formation, emitter wrap through, metallization wrap through, back surface passivation, laser marking or laser cutting.

27. A method according to claim 26, when performed in-line on a solar cell manufacturing line.

28. A method for processing a semiconductor sample, said method comprising the steps of:

(a) while performing a laser processing step on a region of said semiconductor sample, illuminating at least said region with a predetermined illumination to produce photoluminescence from said sample in response to said illumination;

(b) acquiring at least one image of the photoluminescence emitted from said sample; and

(c) processing said at least one image to obtain information on defects in said sample.

29. A method according to claim 28, wherein step (c) comprises obtaining information on defects present in said sample before said laser processing step and/or defects being induced in said sample by said laser processing step.

30. A method according to claim 28 or claim 29, further comprising the step of (d) adjusting a parameter of said laser processing step based on said information.

31. A method according to claim 30, wherein said parameter comprises laser power, pulse repetition rate or scanning rate.

32. A method according to any one of claims 28 to 31, further comprising the step of (e) determining, based on said information, a destination of said sample after completion of said laser processing step.

33. A method according to claim 32, wherein said destination comprises a reject bin, a high quality cell line, a standard quality cell line, or a remediation line.

34. A method according to any one of claims 28 to 33, wherein said defects comprise dislocations, cracks, micro-channels, shunts or areas of reduced minority carrier lifetime.

35. A method according to any one of claims 28 to 34, wherein said semiconductor sample comprises a multicrystalline silicon wafer, a monocrystalline silicon wafer, or a thin film comprising amorphous silicon, crystalline silicon, an amorphous silicon-germanium alloy, a crystalline silicon-germanium alloy, crystalline germanium, cadmium telluride, CIGS, CIS, or a III-V semiconductor based on gallium, aluminium and/or indium arsenide.

36. A method according to any one of claims 28 to 35, wherein said laser processing step occurs during a stage in the manufacture of a solar cell, said stage comprising edge isolation, spot isolation, cell isolation, selective emitter formation, emitter wrap through, metallization wrap through, back surface passivation, laser marking or laser cutting.

37. A method according to claim 36, when performed in-line on a solar cell manufacturing line.

38. A system for processing a semiconductor sample, said system comprising a photoluminescence imaging apparatus and a laser processing station, wherein said photoluminescence imaging apparatus comprises:

    an illumination source for illuminating said sample with a predetermined illumination to produce photoluminescence from said sample in response to said illumination;

    an image acquisition device for acquiring at least one image of the photoluminescence emitted from said sample; and

    a processor for processing said at least one image to obtain information on defects present in said sample or induced in said sample in a laser processing step;

    and wherein said laser processing station comprises:

    a laser for performing a laser processing step on said sample; and

    a controller for controlling said laser.

39. A system according to claim 38, wherein said photoluminescence imaging apparatus and said laser processing station are housed within a common laser safety enclosure.

40. A system according to claim 38 or claim 39, wherein said controller is configured to adjust a parameter of said laser in response to said information on defects present or induced in said sample.

41. A system according to any one of claims 38 to 40, further comprising:

a transport mechanism for transporting said sample from said photoluminescence imaging apparatus to said laser processing station; and

a sample handling mechanism provided between said photoluminescence imaging apparatus and said laser processing station.

42. A system according to claim 41, wherein said sample handling mechanism is configured to direct said sample to a reject bin in response to said information on defects present or induced in said sample.

43. A system according to claim 41, wherein said sample handling mechanism is configured to direct said sample to a remediation line in response to said information on defects present or induced in said sample.

44. A system according to claim 41, wherein said sample handling mechanism is configured to direct said sample to an alternate process line in response to said information on defects present or induced in said sample.

45. A system according to claim 41, wherein said sample handling mechanism is configured to adjust the position or orientation of said sample relative to said laser processing station in response to said information on defects present or induced in said sample.

46. A system according to any one of claims 38 to 40, further comprising:

a transport mechanism for transporting said sample from said laser processing station to said photoluminescence imaging apparatus; and

a sample handling mechanism provided after said photoluminescence imaging apparatus.

47. A system according to claim 46, wherein said sample handling mechanism is configured to direct said sample to a reject bin in response to said information on defects present or induced in said sample.

48. A system according to claim 46, wherein said sample handling mechanism is configured to direct said sample to a remediation line in response to said information on defects present or induced in said sample.

49. A system according to claim 46, wherein said sample handling mechanism is configured to direct said sample to an alternate process line in response to said information on defects present or induced in said sample.

50. A system according to any one of claims 38 to 40, wherein said photoluminescence imaging apparatus and said laser processing station are co-located.

51. A system according to claim 50, further comprising a sample handling mechanism for directing said semiconductor sample to a destination after said sample exits said photoluminescence imaging apparatus and said laser processing station.

52. A system according to claim 51, wherein said sample handling mechanism is configured to direct said sample to a reject bin in response to said information on defects present or induced in said sample.

53. A system according to claim 51, wherein said sample handling mechanism is configured to direct said sample to a remediation line in response to said information on defects present or induced in said sample.

54. A system according to claim 51, wherein said sample handling mechanism is configured to direct said sample to an alternate process line in response to said information on defects present or induced in said sample.

55. A system according to claim 50, further comprising a sample handling mechanism configured to adjust the position or orientation of said sample relative to a subsequent processing station in response to said information on defects present or induced in said sample.

56. A system according to any one of claims 50 to 55, wherein a single optical source serves as said illumination source and as said laser.

57. A system when used to implement the method according to any one of claims 1 to 37.

58. A semiconductor sample when processed by the method according to any one of claims 1 to 37 or the system according to any one of claims 38 to 56.

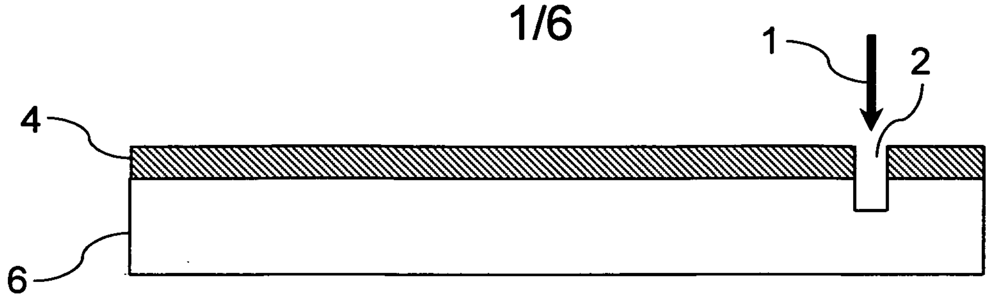

Fig. 1

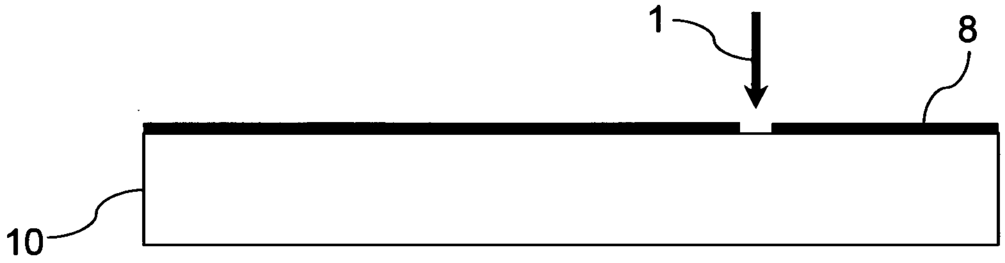

Fig. 2

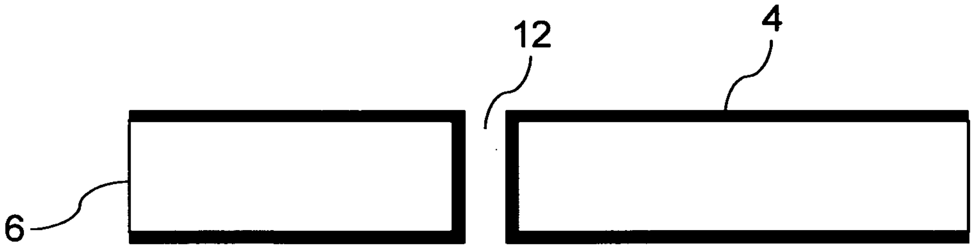

Fig. 3

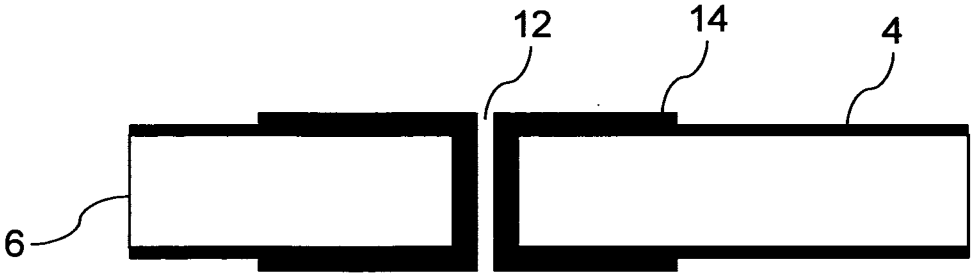

Fig. 4

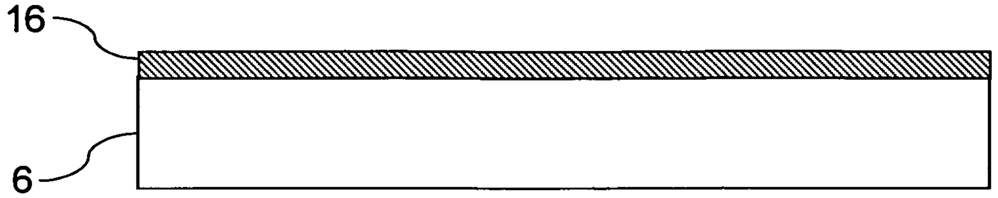

Fig. 5

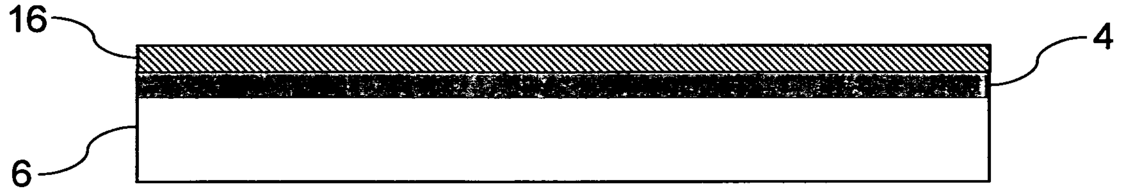

Fig. 6

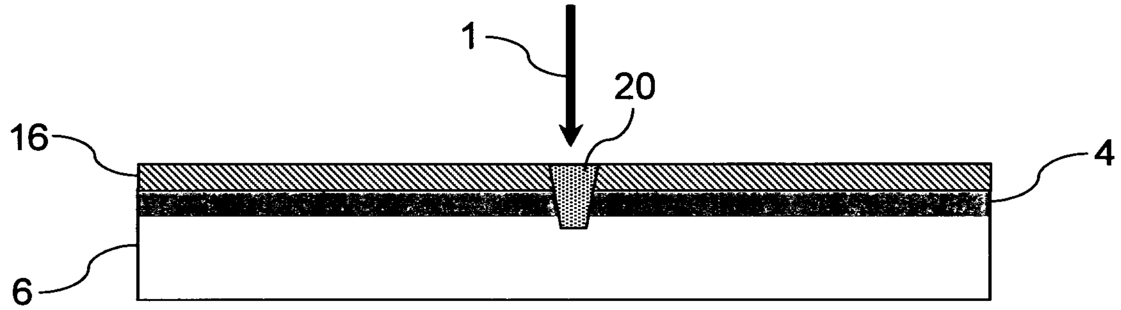

Fig. 7

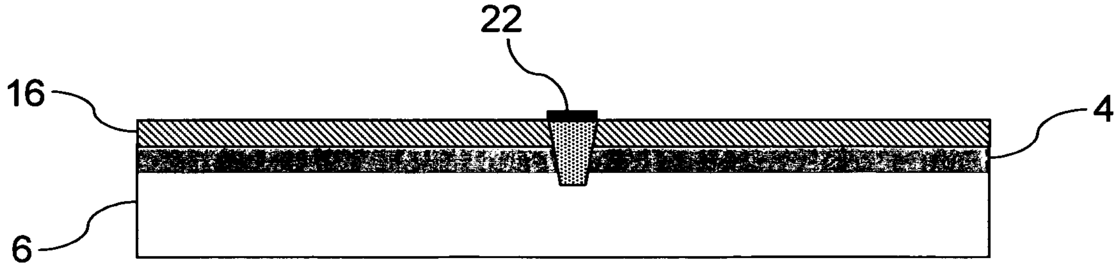

Fig. 8

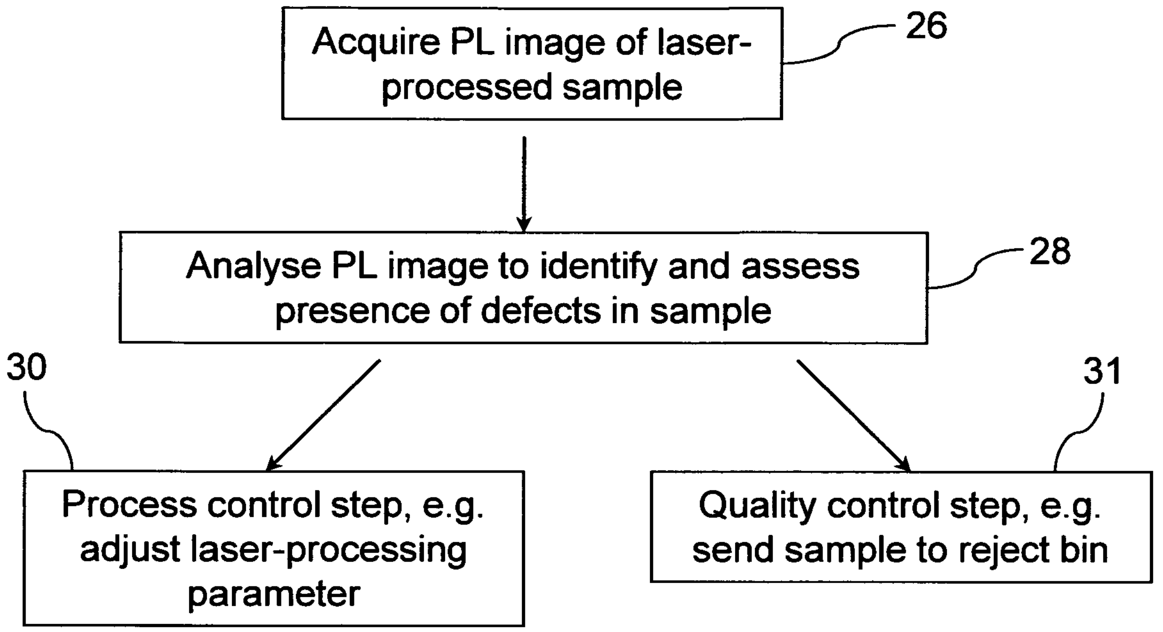
Acquire PL image of laser-processed sample
26
Analyse PL image to identify and assess presence of defects in sample
28
30
31
Process control step, e.g. adjust laser-processing parameter
Quality control step, e.g. send sample to reject bin

Fig. 9

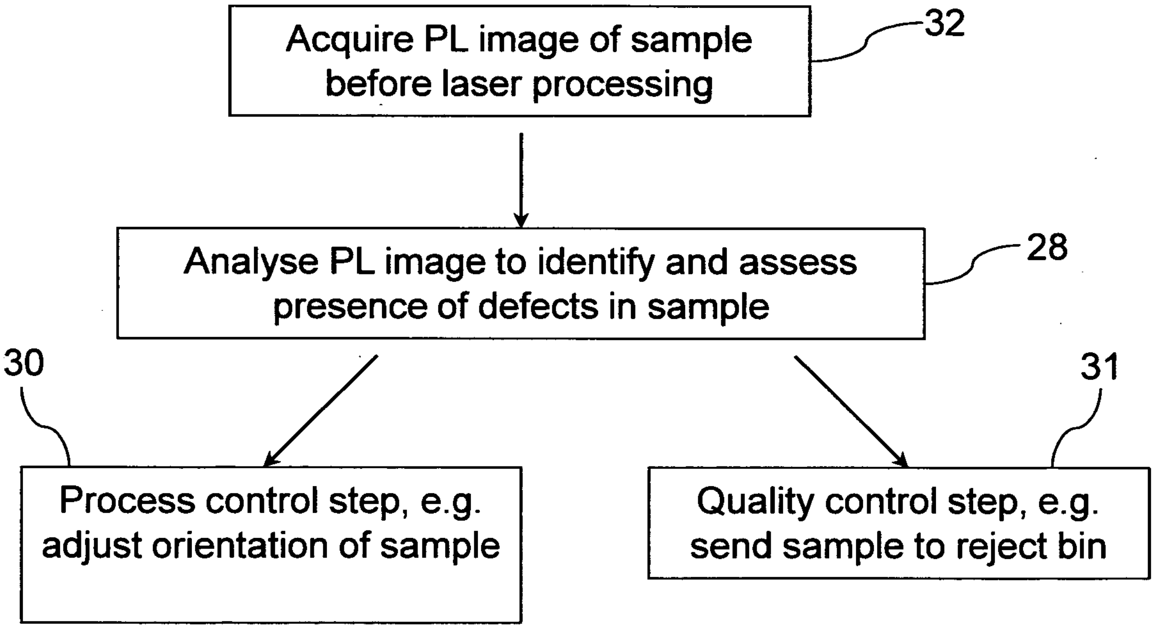
Acquire PL image of sample before laser processing
32
Analyse PL image to identify and assess presence of defects in sample
28
30
31
Process control step, e.g. adjust orientation of sample
Quality control step, e.g. send sample to reject bin

Fig. 10

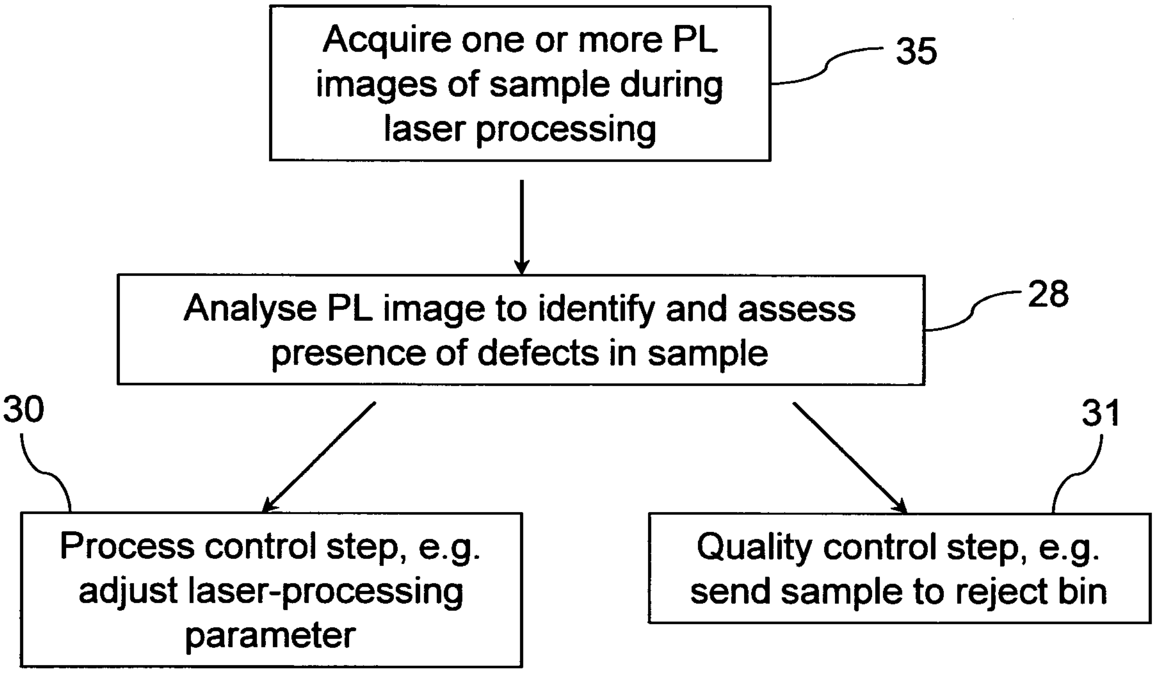
Acquire one or more PL images of sample during laser processing
35
Analyse PL image to identify and assess presence of defects in sample
28
30
31
Process control step, e.g. adjust laser-processing parameter
Quality control step, e.g. send sample to reject bin

Fig. 11

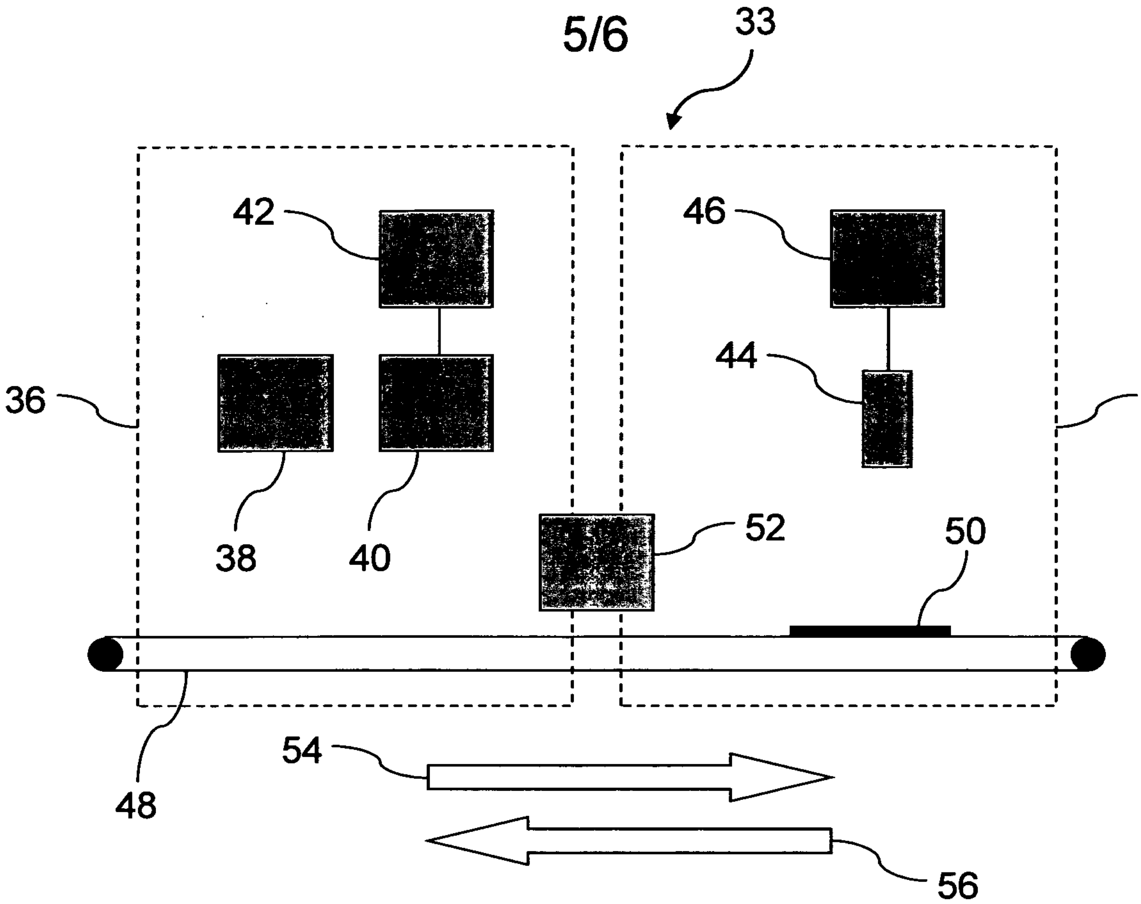

Fig. 12

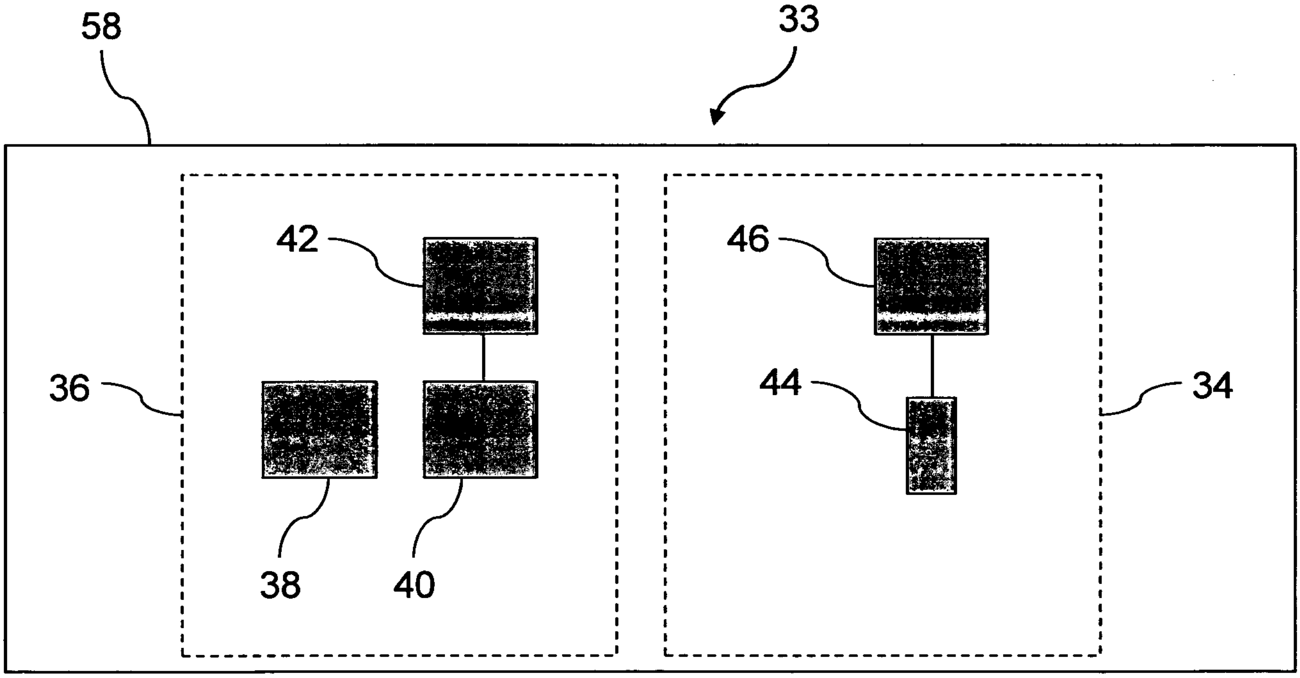

Fig. 13

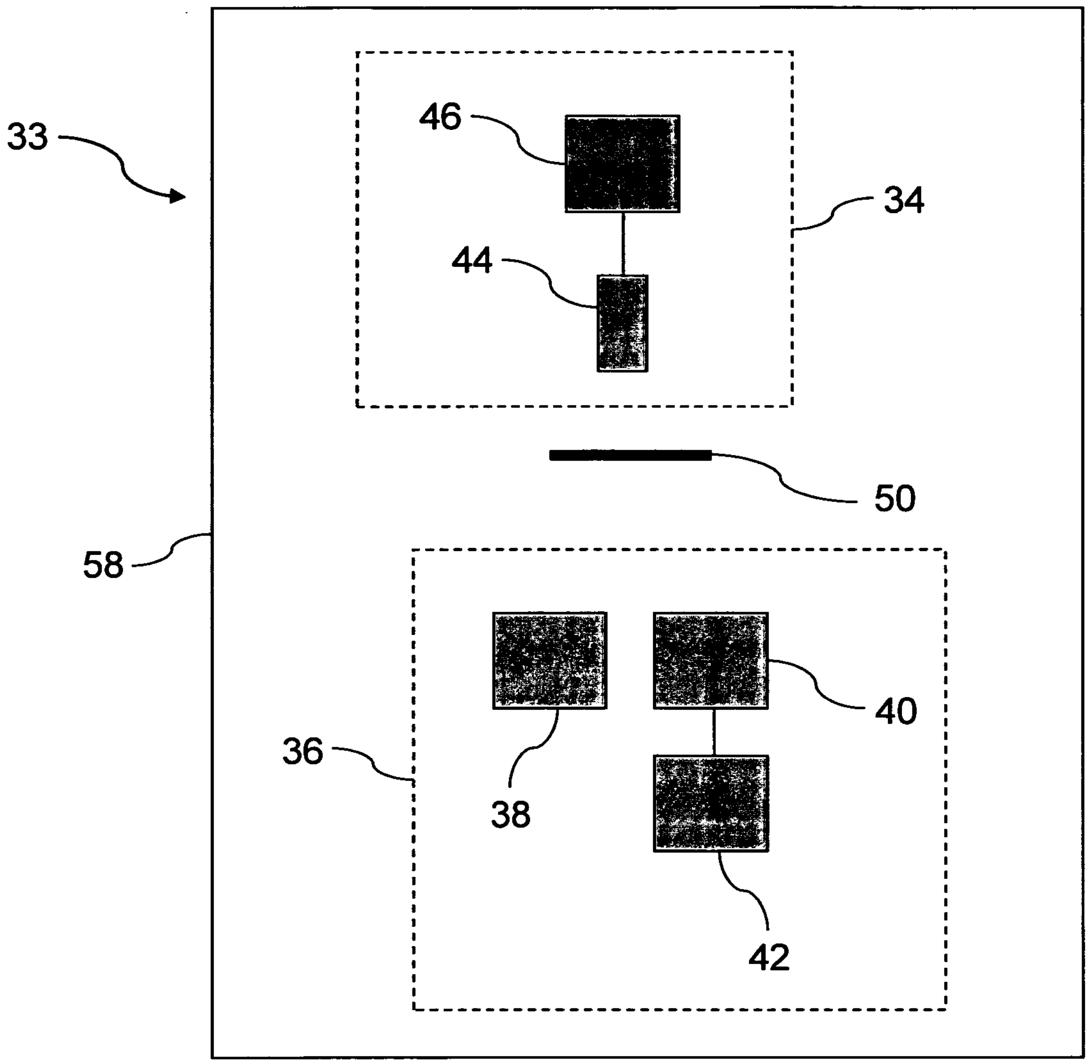

Fig. 14

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2011/000364

A. CLASSIFICATION OF SUBJECT MATTER

H01L 21/66 (2006.01) *G01N 21/95* (2006.01) *G01N 21/64* (2006.01) *H01L 21/67* (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)
EPODOC/DWPI: (IPC/ECLA: H01L21/66, G01N21/95, G01N 21/64) and photoluminescence, quality control, laser etching, edge isolation, defect, rejection, flaw, and similar terms.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	WO 2010/019992 A1 (BT IMAGING PTY LTD) 25 February 2010	
X	Paragraphs 0016, 0023-0026, 0031, 0032, 0037, 0041, 0049, 0051, 0052	1, 2, 5-12, 15-20, 22-30, 32-44, 46-54, 57, 58
Y		3, 4, 13, 21, 31
	WO 2009/026661 A1 (BT IMAGING PTY LTD) 05 March 2009	
X	Pages 2, 7, 10-13; Figure 4	1, 2, 5-12, 15-20, 22-30, 32-44, 46-54, 57, 58
Y		3, 4, 13, 21, 31
	US 2003/0025907 A1 (SAVAREIGO) 06 February 2003	
X	Paragraphs 0007-0009, 0012, 0121, 0145-0146; Figure 13	38-44, 46-54, 56-58
Y		3, 13, 21, 31

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

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search 05 May 2011	Date of mailing of the international search report 10 MAY 2011
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 **GERARD ATKINSON** AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No : +61 2 6283 2089

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2009/121133 A1 (BT IMAGING PTY LTD) 08 October 2009 Paragraphs 0031, 0045-0047; Figure 10; Claim 38	11, 14-17, 38-42, 44-47, 49, 51, 52, 54, 55, 57, 58
Y		4, 13
P, X	WO 2010/088120 A2 (VSERV TECHNOLOGIES CORP) 05 August 2010 Paragraphs 0016 and 0018; Figure 1	1-58
A	US 2002/0182760 A1 (WACK et al.) 05 December 2002 See Whole Document	1-58

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	2010019992	NONE					
WO	2009026661	CN	101861643	EP	2195833	KR	20100075875
US	2003025907	IL	135522	US	2001028454	US	6556293
		US	6621572				
WO	2009121133	AU	2009230877	CN	102017191	EP	2272101
		KR	20100131512	US	2011025839		
WO	2010088120	US	2010182421				
US	2002182760	AU	95060/01	EP	1319244	US	2002107660
		US	6633831	US	6673637	US	6694284
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		US	2002102749	US	6946394	US	2002097406
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		US	7106425	US	2002180961	US	7130029
		US	2002103564	US	7139083	US	2002179864
		US	7196782	US	2002106848	US	7349090
		US	2006072807	US	7460981	US	2004235205
		US	7751046	US	2002190207	US	2004073398
		US	2010271621	WO	0225708		

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

END OF ANNEX