

**A METHOD OF PASSIVATING A PLURALITY OF SOLAR CELLS ARRANGED WITHIN  
AN AT LEAST PARTIALLY MANUFACTURED SOLAR MODULE**

FIELD OF THE INVENTION

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The present invention relates to a method of passivating a plurality of solar cells arranged within a manufactured solar module.

BACKGROUND OF THE INVENTION

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Solar modules for providing electrical energy from sunlight typically include a plurality of solar cells (i.e. photovoltaic cells), each comprising a semiconductor substrate. Specifically, each solar cell may typically include a crystalline silicon wafer which functions as a photoelectric conversion element.

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Each solar module is typically manufactured by arranging the plurality of solar cells together in an array and then electrically connecting them together to define a string. The solar cell strings are laminated between a top plate and a back plate, with an encapsulant interposed therebetween to protect the solar cells from the ingress of moisture. The laminate structure is mounted in a frame and an external electrical connection is provided to enable power to be extracted from the solar cells.

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A general aim for solar module development is to improve the power conversion efficiency of the solar modules, balanced by a need for reduced production costs. Efforts to achieve this have focussed, in particular, on passivating defects which form in the solar cells during their manufacture, and which remain present during the construction of the solar module.

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Known methods of passivating defects in solar cells are carried out during the manufacture of the solar cell, or shortly thereafter. Such methods are carried out on individual solar cells and so must be undertaken in controlled environments to avoid damaging the solar cell.

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Whilst these passivation methods can result in improvements in device performance, there is an ongoing need to improve the passivation of solar cells and thereby improve the performance of the solar module.

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SUMMARY OF THE INVENTION

At their broadest, aspects of the present invention provide a means of passivating a plurality of solar cells arranged within an at least partially manufactured solar module, such that the resulting solar module exhibits increased operating efficiency.

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A first aspect of the present invention provides a method of passivating a plurality of solar cells arranged within an at least partially (e.g., partly) manufactured solar module, wherein the solar module comprises a plurality of solar cells, and an electrical assembly which connects the plurality of solar cells together into one or more strings of solar cells, wherein the electrical  
10 assembly is connectable to an electrical circuit which is external to the solar module. The method comprises: connecting the electrical assembly to an external electrical circuit that comprises a current supplier (e.g., a current supply unit or assembly); and supplying a forward current to the plurality of solar cells using the current supplier; and wherein the step of supplying the forward current is conducted before lamination of the solar module or after  
15 lamination of the solar module.

The supplied forward current is transmitted through to each of the plurality of solar cells arranged in the string of solar cells, which causes passivation of defects in the solar cells. Defect passivation leads to an increase in the open circuit voltage (Voc) and fill factor (FF) of  
20 the solar cells, when in use, which thereby improves the performance of the solar module.

The supplied forward current may also passivate defects within the electrical assembly. For example, by passivating defects at an interface between two components (e.g., two conductive elements) of the electrical assembly, and/or between the electrical assembly (e.g., a  
25 conductive element) and a solar cell of the plurality of solar cells. This increases the extraction of charges by the electrical assembly, which thereby further improves the performance of the solar module.

The method, according to the present invention, enables each of the plurality of solar cells to  
30 be passivated at the same time, and with a single current supplier (e.g. voltage source). Advantageously, the passivation step is conducted before or after lamination of the solar cell (i.e. not simultaneously with a lamination process) because the passivation step yields greater defect removal and thus improvements in efficiency when it is conducted at lower temperatures and/or pressures than are present during lamination.

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The present method also conveniently utilises the existing electrical connections within the solar module (i.e., the solar module electrical assembly) to effect the passivation treatment upon the solar cells. This removes the need for additional electrical connection equipment. Also, the solar module's outer casing provides a protective environment for the plurality of solar cells during the passivation treatment, so that the method can be carried out in a variety of different locations (e.g., in a separate location to a solar module manufacturing facility). Accordingly, the present method increases the efficiency and throughput of solar module manufacturing processes.

When the solar cell is operated under dark conditions (e.g., when light is not incident upon the solar cell), the forward current in the solar cell corresponds to a flow of charge carriers through the solar cell in a direction which is permitted by the in-built photodiode of the solar cell (e.g., which may be formed at a junction between a p-type material and an n-type material). A forward bias may be applied across the solar cell to generate a forward current. In this forward current condition, negative charge carriers (e.g., electrons) flow towards a positive terminal (e.g., a positive electrode) of the solar cell and positive charge carriers (e.g., holes) flow towards a negative terminal (e.g., a negative electrode) of the solar cell. Accordingly, the forward current may define a positive current of the solar cell.

If a reverse bias is applied to the solar cell, a reverse current is achieved which corresponds to a flow of charge carriers through the solar cell in a direction which is not permitted by the in-built photodiode. Accordingly, only a very small reverse current is achieved under such reverse bias and reverse current conditions.

When a solar cell is operated under normal illuminated conditions (e.g., when light is incident upon the solar cell) it is configured to operate with a negative photocurrent that is caused by the absorption of photons. A load is applied to the solar cell in order to generate electrical power, as will be understood by the skilled person.

As described above, the method of the present invention supplies a forward current to the solar cells. This forward current (e.g., the positive current) has the opposite polarity to the normal operating current of the solar cells (e.g., the negative photocurrent). In this way, the method of the present invention may be defined as operating the solar cells with a 'reverse' current (e.g., a forward current) which is in the 'reverse' direction to that which the solar cells experience during their normal operation.

Optional features will now be set out. These are applicable singly or in any combination with any aspect.

5 Lamination of the solar module may comprise applying heat and/or (negative) pressure to a solar cell module comprising a string of solar cells contained in an encapsulant that is interposed between front and back sheets of the solar module. The heat and/or (negative) pressure may be of a sufficient magnitude to bond the solar cell string, encapsulant and front and back sheets together (e.g. a temperature greater than or equal to the melting temperature of the encapsulant (typically 90°C to 160°C) and/or a pressure of less than or equal to -10 KPa  
10 (i.e. a vacuum) (e.g. less than -10 KPa and greater than -95 KPa) or greater than or equal to 10 KPa (e.g. greater than 10 KPa and up to 95 KPa).

By conducting the step of supplying the forward current before or after lamination of the solar module, this method step may not be conducted during lamination of the solar module (e.g.  
15 not conducted during the application of heat and/or pressure to effect lamination).

By conducting the step of supplying the forward current before lamination of the solar module, this method step may be conducted prior to the application of heat from an external heat source to the solar cell string.  
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By conducting the step of supplying the forward current before lamination of the solar module, this method step may be conducted prior to the application of lamination pressure to the solar cell string, for example, prior to application of a (negative) pressure to the solar cell string.

25 By conducting the step of supplying the forward current before lamination of the solar module, the method step may be conducted prior to the solar cell string being interposed between one or more of a front sheet, a back sheet, an upper encapsulant layer and a lower encapsulant layer of a solar cell module.

30 By conducting the step of supplying the forward current before lamination of the solar module, the method step may be conducted prior to the solar cell string being positioned in a pressure chamber or in a press.

By conducting the step of supplying the forward current before lamination of the solar module,  
35 the method step may be conducted immediately subsequently a step of electrically connecting at least two of the plurality of solar cells together to form a string (i.e. without any intervening

steps between the step of electrically connecting the solar cells together and the steps of connecting the electrical assembly to an external electrical circuit that comprises a current supplier and subsequently supplying a forward current to the plurality of solar cells using the current supplier).

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By conducting the step of supplying the forward current after lamination of the solar module, this method step may be conducted after a step of allowing heat from the lamination of the at least partially manufactured solar module to at least partially dissipate (e.g. the steps of connecting the electrical assembly to the external electrical circuit and supplying the forward current may be conducted before any further fabrication steps are conducted after lamination of the solar module).

By conducting the step of supplying the forward current after lamination of the solar module, this method step may be conducted after a step of releasing the laminating pressure applied to the at least partially manufactured solar module, for example, after the release of the vacuum pressure.

By conducting the step of supplying the forward current after lamination of the solar module, this method step may be conducted after a step of allowing an encapsulant layer of the at least partially manufactured solar module to solidify (e.g. after the encapsulant layer temperature has reduced to below the melting temperature of the encapsulant, for example, less than or equal to 120°C, less than or equal to 110°C less than or equal to 100°C, less than or equal to 90°C, or less than or equal to 80°C).

By conducting the step of supplying the forward current after lamination of the solar module, this method step may be conducted after connecting a junction box and/or a junction cable to the solar cell.

The above-described method of passivating a plurality of solar cells arranged within an at least partially manufactured solar module may be referred to herein, and throughout this document, as the passivation method. The passivation method may be conducted when the solar module is in an illuminated state (e.g., under light conditions when the radiation is incident upon the solar cells) and in a non-illuminated state (e.g., under dark conditions when substantially no radiation is incident upon the solar cells). An example of operating the solar cells in dark conditions may involve operating the solar cell in a darkened room or when the solar cell is substantially (e.g., completely) shielded from any incident light. Where the passivation method

is conducted with the solar module in an illuminated state, the forward bias applied to the solar cell is sufficient to overcome the negative photocurrent that would otherwise be generated by the illumination and produce a positive current through the solar module.

- 5 It will be understood that each of the solar cells comprise a junction between two elements which is configured to separate photogenerated charge carriers. The junction may be formed between two semiconductor materials. For example, the junction formed between a positively doped (p-type) semiconductor material and a negatively doped (n-type) material (e.g., to form a p-n junction). Forward biasing the solar cell may involve applying a positive voltage to the p-type material and a negative voltage to the n-type material to establish an electric field across the junction. The electric field generated by the forward bias acts to reduce an inbuilt electric field (e.g. a potential barrier associated with a depletion region formed between the p-n materials) which is formed by the junction. By contrast, the application of a reverse bias increases the inbuilt electric field at the junction. When applying a bias to the solar cell under normal conditions (e.g. room temperature), a current is only established across the junction if the applied voltage is large enough to overcome a barrier potential of the junction (e.g., around 0.7 Volts for a crystalline silicon solar cell). The resulting current may correspond to a diffusion of charge carriers across the junction.
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- 20 The forward current supplied to the solar module may be achieved by applying a potential difference (e.g. a voltage, or bias) to the electrical assembly. The voltage which is applied to the electrical assembly leads to an injection of forward current into the electrical assembly, and thereby to the plurality of solar cells.
- 25 The current supplier may comprise a controllable charge carrier injector. The controllable charge carrier injector may be configured to inject charge carriers into the electrical assembly of the solar module and may be responsive to a control signal received from a controller which is operable by a user of the current supplier. The current supplier may comprise a voltage source. The method may comprise a step of configuring the current supplier to supply a forward current to the plurality of solar cells. This step may comprise configuring the voltage source to apply a forward bias to the electrical assembly to supply the forward current to the plurality of solar cells. In this way, the voltage source may be configured to supply a load current which is injected into the electrical assembly of the solar module.
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The current supplier may be configured to supply a forward current to the plurality of solar cells under forward bias conditions (e.g., by applying a forward bias to the electrical assembly of the solar module).

5 The voltage applied to the electrical assembly may be defined as a passivation voltage of the passivation method. Accordingly, the resulting forward current injected into the plurality of solar cells may define a passivation current of the passivation method. Also, the passivation method may be characterised by a period of time over which the bias is applied to the electrical assembly, which may define a passivation period of the passivation method.

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It will be appreciated that the method according to the present invention involves passivating the plurality of solar cells after they have been at least partially assembled (e.g., at least partially installed) within a solar module.

15 The at least partially manufactured solar module may comprise the plurality of solar cells arranged within an outer casing of the solar module. When the solar cells are arranged within the outer casing of the solar module, the solar module may be a laminated solar module. The electrical circuit may be external to the outer casing of the solar module. The method enables the solar cells to be passivated whilst they are arranged, in situ, within the solar module. By  
20 passivating the solar cells after they have been installed in the solar module, the present method removes the need to passivate the solar cells separately (e.g., before they are manufactured into a solar module).

The plurality of solar cells may be arranged within a laminate structure of the solar module (i.e.  
25 arranged within the outer casing of the solar module). For example, the outer casing may comprise a front sheet and a back sheet, with the plurality of solar cells interposed therebetween. Accordingly, the passivation method may be carried out substantially after the solar cells are arranged (e.g., installed) within the laminate structure of the solar module.

30 The outer casing of the at least partially manufactured solar module may comprise a front sheet and a back sheet. An encapsulant may be interposed with the plurality of solar cells between the front and back sheets of the outer casing. The encapsulant may be heated to bond together the plurality of solar cells and the outer casing to form the at least partially manufactured solar module, as would be understood by the skilled person. The method of  
35 manufacturing the at least partially manufactured solar module may comprise interposing an encapsulant and the plurality of solar cells between the front and back sheets and then heating

the solar module (e.g., the encapsulant) to bond the solar cells to the outer casing (e.g., between the front and back sheet to form a laminate structure). Where the step of supplying the forward current is conducted after lamination of the solar module, the method of passivating the plurality of solar cells may further comprise allowing the heat from the at least partially manufactured solar module to at least partially dissipate from the plurality of solar cells before supplying forward current to the plurality of solar cells.

According to an exemplary arrangement, it will be appreciated that the at least partially manufactured solar module may be defined as being one for which no further heating method steps are required in order to complete the manufacturing process. Hence, substantially all manufacturing steps involving heat may be completed prior to the start of the passivation method. In other embodiments, the at least partially manufactured solar module may be defined as being one where the only further heating method steps required in order to complete the manufacturing process is the soldering of one or more diodes of the electrical assembly to the module/laminate. In other embodiments, the at least partially manufactured solar module may be defined as being one where the electrical connections between the solar cells, and, optionally, between the plurality of strings (where present), have been formed.

The method according to the present invention may comprise supplying forward current to the plurality of solar cells (e.g., applying a voltage, or bias to the electrical assembly) in dependence on the temperature of the plurality of solar cells being at or below a pre-determined temperature. The method may comprise determining the temperature of the plurality of solar cells, and only supplying forward current to the plurality of solar cells if the temperature is below a pre-determined temperature. In this way, the method may include waiting for the heat of the solar module manufacturing process to dissipate, at least partially, before passivating the plurality of solar cells. In an embodiment, the method may involve cooling the solar module to reduce the amount of time between the heating step completing and the passivating step beginning. For example, the cooling process may involve passive cooling elements, such as, heat sinks, and/or active cooling elements, such as, fans to direct an air flow over a surface of the module.

The present inventors have discovered that the method according to the present invention is able to achieve increased passivation of the plurality of solar cells when the method commences with solar cells at an ambient temperature (e.g., room temperature, such as 20°C +/- 5°C). For example, the passivation may be advantageously undertaken when the solar cells are not being heated by an external source and/or when the solar cells do not hold thermal

energy previously absorbed during fabrication of the solar module. However, the passivation method is still able to achieve increased passivation of the plurality of solar cells when the method is conducted with the solar cells at above ambient temperature in comparison to not conducting the passivation method. In particular, commencing the injection of current when  
5 the solar cell is not being heated and/or when the solar cells do not hold thermal energy previously absorbed during fabrication of the solar module (e.g. when the solar cells are at room temperature) may be particularly beneficial where the solar cells are heterojunction (HJT) solar cells.

10 The method may comprise allowing the heat which can build-up during the module manufacturing process to dissipate, before supplying forward current to the solar cells. By contrast, it has been determined that if the passivation treatment is applied shortly (e.g., immediately) after the solar cells are laminated within the solar module (e.g., when the solar cells are still hot), then the effects of the passivation method can be diminished compared to if  
15 the passivation method is conducted once the heat has dissipated from the module.

The step of determining the temperature of the plurality of solar cells may comprise measuring the temperature of a solar cell. For example, directly measuring the temperature of at least one of the solar cells using an infrared sensor, or non-contact thermometer in order to determine  
20 when the forward current should be supplied, as would be readily understood by the skilled person.

Alternatively to measuring the temperature, the method may comprise measuring how much time has passed after the fabrication of the solar module has completed (e.g., after the solar  
25 cells are mounted within the outer casing of the solar module and an external heat source used to bond the outer casing together, and/or to the solar cells, has been removed). The forward bias can be applied once the measured time exceeds a known time value indicative of how long it takes for the solar module's temperature to drop below the pre-determined temperature.

30 In an exemplary arrangement, the method may comprise determining that the temperature of the solar cells is at around room temperature (e.g. around 20°C) before supplying the forward current to the electrical assembly.

The method may comprise applying a voltage such that the magnitude (or absolute value) of  
35 the forward current that is supplied to (e.g., injected into) the electrical assembly is equal to or greater than the magnitude (or absolute value) of a nominal power current,  $I_{mpp}$ , of at least

one of the solar cells of the solar module (i.e. the current through at least one of the solar cells when the power output from the solar cell is at its maximum). In further examples, the magnitude of the forward current supplied to the electrical assembly is greater than or equal to the magnitude of a nominal power current (i.e. the current at the maximum power point) of the solar module. For example, the nominal power current of the solar module may be up to -10 Amperes (optionally up to -10.5 Amperes), such that the magnitude of the nominal power current of the solar module is up to 10 Amperes (optionally up to 10.5 Amperes). In the case of the nominal power current being -10 Amperes, the forward current supplied to the electrical assembly may be at least +10 Amperes. Accordingly, the magnitude of the forward current is at least 10 Amperes, such that the magnitude of the passivating current is greater than or equal to the magnitude of the nominal power current of the solar cell (that is, 10 is equal to 10). In another example, the forward current supplied to the electrical assembly may be +12 Amperes when the nominal power current is -10 Amperes. Accordingly, the magnitude of the passivating current is greater than the magnitude of the nominal power current (that is, 12 is greater than 10).

The method may comprise applying a voltage such that the magnitude of the forward current supplied into the electrical assembly is greater than or equal to the magnitude of the short circuit current of at least one of the solar cells of the solar module, or the magnitude of the short circuit current of the solar module. The short circuit current defines a current value which is the maximum current that the solar cell or module (e.g., the electrical assembly and/or the plurality of solar cells) is designed to conduct during normal use. In this way, the voltage creates a forward current whose magnitude is greater than or equal to the magnitude of the short circuit current of at least one of the solar cells of the module, or greater than or equal to the magnitude of the short circuit current of the solar module.

The method may comprise determining a short circuit current of the solar module, and applying a forward voltage to the electrical assembly to inject forward current into the plurality of solar cells which is greater than the short circuit current.

The forward current supplied to the electrical assembly may be equal to the solar module's short circuit current or greater (e.g. at least 10.5 Amperes). Alternatively, the method may comprise injecting a forward current into the plurality of solar cells which is at least, or around, 314% of the short circuit current of the solar module (e.g. 33 Amperes). The method may comprise injecting a forward current which is at least, or around, 419% of the short circuit current of the solar module (e.g. 44 Amperes). The method may comprise injecting a forward

current which is at least, or around, 476% of the short circuit current of the solar module (e.g. 50 Amperes). The method may comprise injecting a forward current which is at least, or up to, 666% of the short circuit current of the solar module (e.g. 70 Amperes).

5 The method may comprise supplying the forward current to the electrical assembly for a determined period of passivation (e.g., a passivation period). The method may comprise supplying the forward current to the electrical assembly for at least one hundred and twenty minutes (e.g., around 120 minutes or two hours). It has been determined that a passivation treatment of around two hours produces an optimal passivating effect. Alternatively, the  
10 the method may comprise supplying the forward current to the electrical assembly for at least one minute (e.g. around 1 minute), at least five minutes (e.g. around 5 minutes, at least 10 minutes (e.g. around 10 minutes), at least fifteen minutes (e.g., around 15 minutes), at least thirty minutes (e.g., around 30 minutes), or at least sixty minutes (e.g., around 60 minutes).

15 The method may comprise supplying the forward current to the electrical assembly for up to 120 minutes (e.g., up to two hours), alternatively around 120 minutes. By limiting the duration of the passivation treatment to up 120 minutes, this advantageously balances the need to optimise the power output of the solar module with the requirement for time-efficient processing of the solar module.

20 A preferred exemplary method of the present invention may comprise applying a voltage to the electrical assembly to inject a forward current of around 314% of the short circuit current, for a period of up to two hours. For a resulting bi-facial solar module, an increase in power output of 2.9W can be achieved compared to a comparable solar module which is not subjected to  
25 the passivation method. The increase in output from the bi-facial solar module may correspond to an increase of 2.35% in the power compared to the untreated solar module.

An exemplary arrangement of the present invention may provide a solar module passivated according to any one of the previous statements.

30 The solar module may be a crystalline silicon solar cell module, which it will be appreciated defines a solar module in which at least one, or each, of the plurality of solar cells comprises a crystalline silicon substrate which functions as a photoelectric conversion element. The solar module may comprise a plurality of solar cells arranged in an array. As such, the solar cells  
35 may be arranged in an ordered series which extends across a horizontal plane of the solar

module. The array of solar cells may extend in a first direction and a second direction perpendicular to the first direction.

5 The plurality of solar cells may be arranged in substantially the same plane. Accordingly, the solar cells may be arranged in a substantially planar array. The solar cells may each be arranged so that they are aligned within the same reference plane. For example, a first solar cell of the plurality of solar cells may be arranged, e.g. orientated, such that a horizontal plane of the first solar cell is aligned with a horizontal plane of a second solar cell. The reference plane of the first and second solar cells may be substantially aligned (e.g. parallel) with a  
10 horizontal plane of the solar module.

The solar module may comprise a width, a length and a height. The solar module may have a thickness, which is measured in the height direction, which is substantially less than its length and its width. The array of solar cells may be arranged in an array which extends in a  
15 longitudinal (e.g. lengthwise) and/or a transverse (e.g. widthways) direction of the solar module. In embodiments, the solar cells may be arranged in a grid formation, such as a rectangular or square grid pattern.

The plurality of solar cells may each comprise a first and a second surface. The first surface  
20 may be configured to face a radiative source (e.g. the sun) when the solar module is in use. The second surface may be arranged opposite the first surface. The first surface of each of the first and second solar cells may define a front (e.g. frontmost) surface. The second surface of each of the first and second solar cells may define a back (e.g. backmost) surface, such that the front surface is opposite the back surface.

25 Each of the first and second solar cells may be configured with a length, a width and a height. The height (i.e. the thickness) of each solar cell may be less than its respective length and width. The length of each solar cell may be less than the respective width. The barrier film may be configured such that it extends across the entire length and the width of each solar cell.

30 One or more (e.g. all) of the plurality of solar cells may be a HJT solar cell.

The outer casing may comprise a front sheet, or front plate, arranged on a front side of the solar module. The outer casing may comprise a back sheet, or back plate, arranged on a back  
35 side of the solar module. At least one or each of the front sheet and back sheet may be formed of glass. At least one, or each, of the front sheet and back sheet may be transparent. The back

sheet may be reflective. The back sheet may be configured with a reflective surface such that it reflects unabsorbed light back towards the solar cells. That is, the outer casing may be suitable for bifacial and mono-facial solar cells.

5 The outer casing may include a frame, or one or more frame elements. The frame may be configured to hold the components of the solar module in place and to provide sealing around the perimeter of the outer casing components (e.g. the front and back sheets). In embodiments where the solar module comprises a front sheet and a back sheet, the frame may apply a compressive force between the front and back sheet in order to retain the components of the  
10 solar module in position, as would be readily understood by the skilled person.

In embodiments, the solar module may comprise an encapsulant layer, or film. The plurality of solar cells may be sandwiched (e.g., interposed) between a front encapsulant and a back encapsulant. The front and back encapsulants may be sandwiched between the front sheet  
15 and the back sheet. The, or each, encapsulant(s) may be arranged to extend in both the first and second directions of the solar module so as to overlay the plurality of solar cells. The encapsulant may extend in a longitudinal (i.e. lengthwise) direction from one lateral end of the solar module to an opposite lateral end of the solar module. The encapsulant may extend in a transverse (e.g. widthways) direction from one longitudinal end of the solar module to an  
20 opposite longitudinal end of the solar module. The front and back encapsulants may be formed of the same material (e.g. EVA). The front and back barrier films may be formed of the same material (e.g. TPO).

The electrical assembly may comprise at least one conductive element (e.g., an electrically  
25 conductive element) configured to electrically connect a first solar cell of the plurality of solar cells to a second solar cell of the plurality of solar cells. The electrical assembly may comprise at least one conductive element in the form of an inter-connector (e.g. a ribbon connector), which may be configured to connect between electrodes arranged on the surface of the solar cells (e.g. printed or plated electrodes, for example, printed or plated busbars). The at least  
30 one conductive element may define a foil-wire electrode assembly, as is explained in more detail below. In this way, the electrical assembly of the solar module is configured to provide an electrical connection between the plurality of solar cells in the solar module.

The electrical connections within the solar module (e.g., which are provided by the at least one  
35 conductive element) may be configured to withstand up to at least forty-five Amperes of applied

forward current. Typically, a junction box and/or a junction cable of the electrical assembly is the limiting factor on the forward current that can be applied to the solar module.

5 The electrical assembly may be configured to electrically connect at least two of the plurality of solar cells together to form a string. The solar cells within the string may be connected in series. The solar module may comprise a plurality of solar cell strings. The solar cell strings may be electrically connected by the electrical assembly (e.g., by a conductive element of the electrical assembly). The solar cell strings may be connected in parallel.

10 The electrical assembly may be configured to form an electrical connection between the plurality of solar cells arranged within the solar module and an electrical circuit which is arranged external to the solar module. In embodiments the electrical assembly may be configured to provide an electrical connection between two solar modules. The electrical assembly may comprise at least one external connector, which physically extends from inside  
15 the solar module (e.g., from an interior of the outer casing) to outside the solar module (e.g., to an exterior of the outer casing). The external connector may pass through an opening, or terminal, in the outer casing of the solar module (e.g., an opening in the back sheet of the outer casing). The external connector may be connectable to the electrical circuit, as would be understood by the skilled person.

20 The electrical assembly may comprise at least one junction box arranged on an external surface of the solar module (e.g., positioned on an external surface of the outer casing). The junction box may be arranged on the back surface of the solar module (e.g., on a back surface of the back sheet). The junction box may be arranged substantially near (e.g., adjacent) to an  
25 opening in the outer casing through which the external connector exits the solar module. The junction box may be arranged to substantially cover (e.g., seal) the opening in the outer casing to prevent moisture from entering the outer casing through the opening.

30 The junction box may be configured to house at least one connection point of the electrical assembly, which enables the solar module to be detachably connected to another solar module and/or to an external electrical circuit. The at least one connection point may define a plug and socket connection between the external connector of the electrical assembly and the external electrical circuit, as would be readily understood by the skilled person. The electrical connector may comprise a junction cable extending away from the junction box, the junction cable  
35 providing a mechanism for connecting the solar module to an external device, such as another solar module.

The junction box may comprise (e.g., house) one or more electronic components of the electrical assembly. For example, the electrical assembly may comprise one or more diodes which control the flow of electricity to the plurality of solar cells (e.g., in the case of partial shading of some of the solar cells). The electrical assembly may comprise a fuse assembly (e.g., a fuse) which is configured to provide overcurrent protection to the solar cells. The fuse assembly may be rated to an overcurrent value of twenty-five Amperes. The junction box may be filled (e.g., at least partially filled) with a sealant to prevent moisture entering the junction box and/or the interior of the solar module.

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The junction box of the electrical assembly may be configured to withstand up to at least forty-five Amperes of applied forward current.

According to an exemplary arrangement, there may be provided a system for passivating a plurality of solar cells arranged within an at least partially manufactured solar module, wherein the manufactured solar module comprises: a plurality of solar cells, and an electrical assembly that connects the plurality of solar cells together into one or more strings of solar cells, wherein the electrical assembly is connectable to an electrical circuit which is external to the solar module. The system comprises: an external electrical circuit which is connectable to the electrical assembly of the solar module, wherein the external electrical circuit comprises a current supplier. The current supplier is configured to supply a forward current to the plurality of solar cells before lamination of the solar module or after lamination of the solar module.

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The external electrical circuit may comprise a plurality of conductive wires, or cables, which are connectable to the electrical assembly of the solar module. The electrical circuit may be external to the outer casing of the solar module.

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The at least partially manufactured solar module may comprise the plurality of solar cells arranged within an outer casing of the solar module.

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The current supplier may comprise a voltage source which may be configured to supply (e.g., inject) the electrical current into the electrical assembly of the solar module. The voltage source may comprise a power converter (e.g., a direct current (DC) power supply unit) which is connectable to an alternating current (AC) power grid. Alternatively, the voltage source may comprise a battery. The voltage source may comprise a controller, or control unit, which is configured to control the output of the voltage source. The voltage source may comprise a

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positive terminal and a negative terminal for connecting to the electrical circuit, as would be understood by the skilled person.

5 In the proceeding paragraphs, any reference to 'the solar cell' will be understood as referring to at least one of the plurality of solar cells. The solar cell may comprise a plurality of elements, each comprising a semiconductor material (e.g., semiconductor layers). The plurality of elements may define a layered structure of the solar cell. At least one or each of the plurality of elements may be configured with a determined conductivity type (e.g. p-type or n-type). In some cases, the semiconductor material may not be doped (e.g. such as with an intrinsic passivation layer).

10 The layered structure may comprise a semiconductor substrate, which may be formed of crystalline silicon (e.g. a monocrystalline silicon wafer). The substrate may be configured with a first conductivity type (e.g. n-type) and the layered structure may comprise a collector layer which is configured with a second conductivity type (e.g. a p-type) that is opposite the first conductivity type, and thus forms a p-n junction with the substrate. According to such an arrangement, the collector layer may define a minority charge carrier collector layer (e.g. a hole-collector layer) of the solar cell.

20 During operation of the solar cell, a plurality of electron-hole pairs are produced by light incident on the substrate. When the substrate is n-type and the minority charge carrier collector layer is p-type (e.g. a hole-collector layer), the separated holes and electrons move to the p-type hole-collector layer and the n-type substrate, respectively. Accordingly, the holes operate as majority charge carriers in the p-type hole-collector layer, and the electrons operate as majority charge carriers in the n-type substrate.

30 According to an alternative arrangement, the substrate may be p-type and the minority charge carrier collector layer may be n-type (e.g. an electron-collector layer), thus forming a p-n junction with the substrate. In this instance, the separated electrons and holes move to the n-type electron-collector layer and the p-type substrate, respectively.

35 The collector layer may define a majority charge carrier collector layer configured with the first conductivity type (e.g. n-type), which is the same as that of the substrate. For example, both the substrate and the majority charge carrier collector layer may be n-type, such that the majority charge carrier collector layer defines an electron-collector layer. As such, the majority charge carrier collector layer may be configured to selectively screen, or extract, charge

carriers from the substrate. Accordingly, when the solar cell is in use, the electrons produced by light incident on the substrate may be collected in the electron-collector layer, wherein they operate as majority charge carriers.

5 The first collector layer may be arranged on a first surface of the substrate. The layered structure of the solar cell may further comprise a second collector layer (e.g. a back-field layer), arranged on a second surface of the substrate, opposite the first surface. Alternatively, both the first collector layer and second collector layer may be arranged on the same surface of the substrate, e.g. on the second (back) surface of the substrate (e.g. in the case of interdigitated  
10 back contact solar cells). The first and second surfaces may define the front and back surfaces of the substrate, respectively. The layered structure of the solar cell may further comprise a passivation layer arranged between the substrate and the respective first and second collector layers, or, where the first and second collector layers are both provided on the same surface of the substrate (e.g. the second surface), the passivation layer may be arranged on the  
15 opposite surface (e.g. the first surface).

According to an exemplary arrangement, the substrate may be formed from an n-type monocrystalline silicon wafer, which exhibits longer minority carrier lifetime characteristics compared to a p-type monocrystalline silicon wafer. The first collector layer (e.g. the front  
20 collector layer) may comprise an amorphous material (e.g. amorphous silicon) which is at least partially doped so as to be p-type. The second collector layer (e.g. the back-collector layer) may comprise an amorphous material (e.g. amorphous silicon) which is at least partially doped so as to be n-type. Alternatively, the first collector layer (e.g. the front collector layer\_ may comprise an amorphous material (e.g. amorphous silicon) which is at least partially doped so  
25 as to be n-type and the second collector layer (e.g. the back-collector layer) may comprise an amorphous material (e.g. amorphous silicon) which is at least partially doped so as to be p-type.

Such an arrangement may contribute towards the formation of a heterojunction technology  
30 (HJT) type solar cell, which is so defined because it combines two different materials to create a charge separating p-n junction. Alternatively, the solar cell may comprise a multi-junction (e.g. tandem) solar cell, which is so defined because it comprises two or more charge separating junctions and two or more charge-generating photon absorbing layers

The solar cell may comprise an electrode arranged opposite the layered structure and configured to extract photo-generated charge carriers from the solar cell. The electrode may be arranged such that the collector layer is interposed between the electrode and the substrate.

5 When the collector layer is arranged on a back (e.g. backmost) surface of the substrate, the electrode may be arranged on a back surface of the layered structure, to define a back electrode of the solar cell. When the collector layer is arranged on a front (e.g. frontmost) surface of the substrate, the electrode may be arranged on a front surface of the layered structure, to define a front electrode of the solar cell. The solar cell may comprise a positive  
10 electrode arranged on the same surface of the layered structure as the p-type collector layer and a negative electrode arranged on the same surface of the layered structure as the n-type collector layer. Each electrode may be configured to form an ohmic contact with the surface of the respective collector layer.

15 The positive and negative electrodes may each comprise a plurality of finger electrodes which are arranged on the surface of the respective collector layer of the solar cell, as will be readily understood by the skilled person. The finger electrodes within each of the pluralities of positive and/or negative finger electrodes may extend in a transverse direction which is parallel with the width direction of the solar cell. The finger electrodes in each plurality may be substantially  
20 parallel to one another. Accordingly, the plurality of negative finger electrodes may form an array of parallel, longitudinally spaced (e.g. equally spaced) finger electrodes. Accordingly, the plurality of positive finger electrodes may form an array of parallel, longitudinally spaced (e.g. equally spaced) finger electrodes.

25 The positive and/or negative electrodes may comprise one or more conductive elements (e.g. elongate busbars), arranged on top of the finger electrodes. The conductive elements may extend in a longitudinal direction which is parallel with the length direction of the solar cells (e.g., perpendicular to the finger electrodes). In this way, the plurality of finger electrodes may be interposed between the one or more elongate busbars and the substrate. The plurality of  
30 elongate busbars and finger electrodes may each be formed of an electrically conductive material such that they enable the flow of electrical charge carriers from the surface of the solar cell to the external circuit. In this way, each one of the busbars and finger electrodes may define a current collector of the electrode.

35 The one or more elongate busbars may be configured to form an electrical connection between the finger electrodes and the electrical assembly of the solar module. The plurality of busbars

of one solar cell may be electrically coupled to the plurality of busbars of a second solar cell by at least one interconnector (e.g., a ribbon connector), as would be readily understood by the skilled person. Accordingly, the at least one interconnector may define at least a part of the electrical assembly of the solar module.

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Alternatively, instead of connection by ribbon connectors, the solar cells may be connected by foil-wire connectors, as would be understood by a person having ordinary skill in the art. The foil-wire connectors may form part of the electrical assembly of the solar module. Each foil-wire connector may comprise a conductive element (e.g. a wire, or wire-portion) which forms part of the electrical assembly of the solar module. A first plurality of conductive wire portions may be arranged on the first surface of the first solar cell. The first plurality of conductive wire portions may be electrically coupled to a second plurality of conductive wire portions arranged on the second surface of the second solar cell. In an embodiment, the first plurality of conductive wire portions may be integral with the second plurality of conductive wire portions.

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In the case of foil-wire connector, at least one, or each, of the plurality of conductive elements may be arranged in and/or on a film. The film may be configured to be insulating and/or optically transparent. The film may be configured to provide adhesion between the solar cell and the conductive element so that the conductive element is correctly spaced on the solar cell. In this way, the film enables the conductive elements to be correctly aligned with the solar cell. The film may provide a mechanical connection between the conductive element and the solar cell.

20

According to an exemplary arrangement, each of the plurality of solar cells may comprise a layered structure comprising a n-type substrate, a p-type hole-collector (or hole-collector layer) arranged on a rear surface of the substrate and a n-type electron-collector (or electron-collector layer) arranged on a front surface of the substrate (e.g., opposite the p-type hole-collector). The hole-collector may be electrically connected to a positive electrode, which is arranged such that the hole-collector is arranged between the positive electrode and the substrate. The electron-collector may be electrically connected to a negative electrode, which is arranged such that the electron-collector is arranged between the negative electrode and the substrate.

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According to a second aspect of the present invention, there is provided a method of at least partially manufacturing a solar module, wherein the method comprises: connecting a plurality of solar cells to an electrical assembly such that the plurality of solar cells are connected together in one or more strings, the electrical assembly being connectable to an electrical circuit that is external to the solar module; and passivating the plurality of solar cells arranged

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within the at least partially manufactured solar module according to any one of the preceding statements.

5 The method may further comprise laminating the solar module; and the step of supplying the forward current as part of the passivating the plurality of solar cells may be conducted before or after the step of laminating the solar module.

10 The step of laminating the solar module may comprise applying heat (and/or (negative) pressure) to a solar cell module comprising a string of solar cells contained in an encapsulant that is interposed between front and back sheets of the solar module. The heat and/or (negative) pressure may be of a sufficient magnitude to bond the solar cell string, encapsulant and front and back sheets together (e.g. a temperature greater than or equal to the melting temperature of the encapsulant (typically 90°C to 160°C) and/or a pressure of less than or equal to -10 KPa (i.e. a vacuum) (e.g. less than -10 KPa and greater than -95KPa) or greater  
15 than or equal to 10KPa (e.g. greater than 10 KPa and up to 95 KPa)).

The method of at least partially manufacturing the solar module may further comprise arranging the plurality of solar cells within an outer casing of the solar module.

20 Where the method comprises arranging the plurality of solar cells within an outer casing of the solar module, the method of at least partially manufacturing the solar module (e.g., the solar module manufacturing process) may further comprise applying heat (and/or (negative) pressure) towards the outer casing to bond the solar cells within the solar module (e.g., a lamination process). The method may comprise allowing the heat from the solar module  
25 manufacturing process to at least partially dissipate from the plurality of solar cells before supplying forward current to the plurality of solar cells.

30 For example, the outer casing may comprise a front sheet and a back sheet. In which case the method of at least partially manufacturing the solar module may comprise interposing an encapsulant of the solar module and the plurality of solar cells between the front sheet and back sheet of the outer casing; and heating the encapsulant to bond the solar cells within the outer casing. The method of passivating the plurality of solar cells may comprise allowing the heat from the heating of the encapsulant to at least partially dissipate from the plurality of solar cells before supplying forward current to the plurality of solar cells.

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It will be understood that the terms 'conductive' and 'insulating' as used herein, are expressly intended to mean electrically conductive and electrically insulating, respectively. The meaning of these terms will be particularly apparent in view of the technical context of the disclosure, being that of photovoltaic solar cell devices. It will also be understood that the term 'ohmic contact' is intended to mean a non-rectifying electrical junction (i.e. a junction between two conductors which exhibits a substantially linear current–voltage (I-V) characteristic).

The skilled person will appreciate that except where mutually exclusive, a feature or parameter described in relation to any one of the above aspects may be applied to any other aspect. Furthermore, except where mutually exclusive, any feature or parameter described herein may be applied to any aspect and/or combined with any other feature or parameter described herein.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Aspects and embodiments of the invention will now be described by way of example with reference to the accompanying drawings in which:

Figs. 1 and 2 show plan and sectional side views of a solar module comprising a plurality of solar cells, respectively;

Fig. 3 shows a system for passivating the plurality of solar cells arranged in the solar module of Fig. 1;

Fig. 4 is a flowchart illustrating a method of passivating the plurality of solar cells arranged within the solar module of Fig. 1;

Fig. 5 is a current-voltage curve for a solar module operating in both dark and illuminated conditions; and

Figs. 6 to 10 show performance data of solar modules which have undergone the passivation method of Fig. 4.

#### DETAILED DESCRIPTION

Aspects and embodiments of the present disclosure will now be discussed with reference to the accompanying figures. Further aspects and embodiments will be apparent to those skilled in the art.

5 The present invention is directed, primarily, towards a system and method for passivating a plurality of solar cells arranged within a manufactured solar module. To provide context for these aspects of the invention, an exemplary arrangement of the manufactured solar module 10 will first be described with reference to Figs. 1 and 2.

10 Fig. 1 and Fig. 2 illustrate the manufactured solar module 10, or solar module assembly, which includes an array of solar cells 12 arranged in a grid-like pattern within an outer casing 14. The solar module 10 is a crystalline silicon solar cell module, which it will be appreciated defines a solar module 10 in which each of the solar cells 12 has a crystalline silicon substrate which functions as a photoelectric conversion element.

15 The outer casing 14 includes a transparent glass sheet 24a at a front side 26 of the solar module 10 and a reflective back sheet 24b arranged at a rear side 28 of the solar module 10. As such, the reflective back sheet 24b and the transparent glass sheet 24a define front and back outer casings of the solar module 10, respectively. The solar cells 12 are sandwiched  
20 between the front and back outer casings as is shown in Fig. 2.

The outer casing 14 further comprises a rectangular frame 102, which extends about a periphery of the solar module 10. The frame 102 protects the edges of the solar module 10 and provides a means for mounting the solar module 10 to a structure (e.g. a building roof).  
25 The frame 102 comprises four elongate frame members 104 that are each mounted to, and extend along, a respective edge of the solar module 10.

Fig. 1 illustrates the top (front) view of the solar module 10, whereas Fig. 2 depicts a transverse section of the solar module 10 taken along the dashed line A-A', as shown in Fig. 1. The solar  
30 module 10 has a length which is the horizontal dimension of Fig. 1, and a width which is the vertical dimension of Fig. 1.

Fig 2 depicts a plurality of solar cells 12 arranged in a substantially horizontal reference plane RP of the solar module 10. The reference plane RP is substantially parallel to the front and  
35 back sheets 24a, 24b of the solar module 10 and extends substantially centrally therebetween. Although, in the presently described embodiment the solar module 12 is shown (in Fig. 1, for

example) as having fifty four solar cells 12, it will be appreciated that this arrangement is just one of many possible configurations, without departing from the scope of the present invention.

5 The dashed arrows at the top of Fig. 2 show the direction of the solar radiation which is incident upon the solar module 10. Each of the solar cells 12 has a front surface 16 (upon which light is incident in normal use) and a rear surface 18 opposite the front surface 16. The front surface 16 is configured in use to substantially face the sun.

10 The solar cells 12 are sandwiched between a pair of encapsulant layers 20a, 20b, which extend across the solar module 10 (in a horizontal direction as shown in Fig. 1), from one side of the solar module 10 to the other. The solar cells 12 are arranged in a planar array which extends in both a lengthways and a widthways direction of the solar module 10, as shown in Fig. 1. The encapsulant layers 20a, 20b extend in both the lengthwise and widthways directions to overlay the plurality of solar cells 12 in the array.

15 With reference to Fig. 2, the solar module 10 includes an electrical assembly 30 which connects the plurality of solar cells 12 together. The electrical assembly 30 is also connectable to an electrical circuit which is external to the outer casing 14 of the solar module 10. In this way, the electrical assembly 30 may be configured to provide an electrical connection between  
20 two solar modules 10.

The solar cells 12 are arranged in rows which extend across the width of the solar module 10. The solar cells 12 in each row are connected in series by the electrical assembly 30 to form a string. Each of the strings are electrically connected in parallel (not shown) by the electrical  
25 assembly 30, as will be readily understood by the skilled person.

The electrical assembly 30 includes a plurality of foil-wire connectors 32 for connecting the solar cells 12 together. Each foil-wire connector 32 includes a plurality of parallel conductive elements (e.g. wires, or wire-portions) which form an electrical connection between two  
30 adjacent solar cells 12. A first end of each of the plurality of conductive elements is overlaid onto the front surface 16 of a first solar cell whilst a second end of the conductive elements is arranged on the back surface 18 of a second solar cell, as shown in Fig. 2.

35 The conductive elements of the foil-wire connectors 32 are arranged in a film (not shown), which is configured to be insulating and optically transparent. The film also adheres the

respective ends of the conductive elements to the solar cells 12, so that the foil-wire connectors 32 are correctly aligned with the solar cells 12.

5 The electrical assembly 30 includes external connectors 34, which extend from inside the solar module 10 (e.g., from an interior of the outer casing 14) to outside the solar module (e.g., to an exterior of the outer casing 14). The external connectors 34 pass through openings 36, or terminals, in the back sheet 24b of the outer casing 14, as shown in Fig. 2. The external connectors 34 are configured to form a connection, at one end, to the foil-wire connectors 32 located at the lateral ends of the solar cell string, and at an opposite end, the external  
10 connectors 34 are connectable to an external electrical circuit.

The electrical assembly 30 includes junction box 38 which is arranged on the back surface of the back sheet 24b of the outer casing 14 of the solar module 10. The junction box 38 is arranged to cover, and thereby seal, the openings 36 in the outer casing 14 through which the  
15 external connectors 34 exit the solar module 10 to prevent moisture from entering the outer casing 14 through the openings 36.

A system 100 for passivating the plurality of solar cells 12 within a manufactured solar module 10 according to an aspect of the present invention will now be described with reference to Figs.  
20 3 and 4. The manufactured solar module 10 is configured as described above in relation to Figs 1 and 2. The system 100 includes an external electrical circuit 42 which is connectable to the electrical assembly 30 (not shown in Fig. 3) of the solar module 10. The external electrical circuit 42 includes a voltage source in the form of a power supply unit 44. The power supply unit 44 is configured to apply a voltage to the electrical assembly 30 to thereby inject a forward current into the plurality of solar cells 12 (not shown in Fig. 3) which are arranged within the  
25 manufactured solar module 10. The forward current causes passivation of defects in the solar cells, which leads to an increase in the open circuit voltage (Voc) and fill factor (FF) of the solar cells, when in use, which thereby improves the performance of the solar module.

30 The external electrical circuit 42 includes a pair of conductive wires 46, which are connected at one end to the junction box 38 of the solar module 10 and at an opposite end to the power supply unit 44. The junction box 38 includes a set of connection points 48 which define positive and negative terminals of the electrical assembly 30 (as indicated by the '+' and '-' labels). The power supply 44 includes a corresponding set of positive and negative terminals 50, with  
35 which the conductive wires 46 of the external circuit 42 form a connection.

The power supply unit 44 receives electrical power from an AC power grid (not shown). The power supply unit 44 includes a transformer assembly which is configured to regulate the power which is received from the AC power grid and thereby control the power (e.g., the voltage/current) which is outputted to the solar module 10. The power supply unit 44 includes  
5 a controller (not shown) which is configured to receive commands from a user of the system 100 and is configured to control the transformer assembly to adjust the power which is outputted to the solar module 12, based on the user commands.

As described above, the system 100 is used to passivate defects in the solar cells 12 of a  
10 manufactured solar module 10. An exemplary passivation method will now be described with reference to Figs. 3 and 4.

A first method step 202 involves providing a manufactured solar module 10 including a plurality of solar cells 12, as described above with reference to Figs. 1 and 2, wherein the plurality of  
15 solar cells 12 are connected by an electrical assembly 30 of the solar module 10.

The passivation method 200 proceeds with a second method step 204, in which the electrical assembly 30 of the solar module 10 is connected to an external electrical circuit 42 of the passivation system 100. Specifically, this second method step 204 involves coupling the  
20 junction box 38 of the electrical assembly 30 to the conductive wires 46 of the external electrical circuit 42 of the passivation system 100, as shown in Fig. 3. This establishes an electrical connection between the power supply unit 14 of the passivation system 100 and the solar cells 12 arranged within the solar module 10.

Once the solar module 10 is electrically coupled to the passivation system 100, the method  
25 proceeds with a third method step 206, in which the voltage source (e.g., the power supply unit 44) is configured to apply a voltage to the electrical assembly 30, which causes an injection of forward current into the plurality of solar cells 12. The power supply unit 44 is controlled by the control unit (not shown) to apply a voltage 10 for a period of time, until the passivation of the  
30 solar cells 12 is completed (e.g., the passivation period). Further, the magnitude of the voltage outputted by the passivation system 100 (e.g., the passivation voltage) and the duration of time over which the voltage is applied to the solar module 10 (e.g., the passivation period) each define controllable variables of the passivation method 200.

Alternatively, the passivation system 100 may be configured to apply the forward current (e.g., the passivation current) to the solar module 10 by any suitable means, as will be understood by the skilled person.

5 To clarify what is meant by the term 'forward current', as applied during the above-described passivation method, the forward current will now be described with reference to Fig. 5, which shows an exemplary current-voltage (I-V) curve for the solar module 10 operating in both dark and illuminated conditions (corresponding to the solid and dashed lines, respectively).

10 When the solar module 10 is operated under dark conditions (e.g., when light is not incident upon the solar cells 12), the forward current in the solar cell corresponds to a flow of charge carriers through the solar cells 12 in a direction which is permitted by the in-built photodiode of the solar cell (e.g., as defined by the p-n junction).

15 A forward bias is applied across the solar cells to generate a forward current (represented by the solid line above the horizontal axis in Fig. 5). In this forward current condition, negative charge carriers (e.g., electrons) flow towards the positive electrode of the solar module and positive charge carriers (e.g., holes) flow towards the negative electrode. In this way, the forward current defines a positive current flowing through each of the solar cells 12.

20 If a reverse bias is applied to the solar cell when not illuminated, a reverse current is obtained (as shown by the solid line to the left of the vertical axis and below the horizontal axis in Fig. 5). This reverse bias condition corresponds to a flow of charge carriers through the solar cell in a direction which is not permitted by the in-built photodiode. Accordingly, only a very small reverse current is achieved under such reverse current conditions.

25 When a solar module 10 is operated under normal illuminated conditions (e.g., when light is incident upon the solar cell) a negative photocurrent is established in the solar cells 12 caused by the absorption of photons (as represented by the dashed line below the horizontal axis in Fig. 5). A forward bias is generated in the solar cell (as represented by the dashed line on the right of the vertical axis in Fig. 5), as will be understood by the skilled person. A load can be applied to the solar cell in order to generate electrical power.

30 The method of the present invention involves supplying a forward current to the solar cells 12. This forward current (e.g., the positive current) has the opposite polarity to the normal operating current of the solar cells (e.g., the negative photocurrent). In this way, the method of the

present invention may be defined as operating the solar cells with a ‘reverse’ current (e.g., a forward current) which is in the ‘reverse’ direction to that which the solar cells experience during their normal operation (i.e. when illuminated).

5 Each of the controllable variables can be controlled (e.g., by the passivation system 100) in order to optimise the passivation of a particular solar module 10. To demonstrate the beneficial effects of the passivation method 200, a series of experiments have been conducted in which pre-manufactured solar modules 10 are passivated according to the passivation method 200, wherein the controllable variables are adjusted for each module so as to produce different  
10 passivation conditions. The results of experiments are shown graphically in Figs. 6 to 10.

In a first Experiment A, nine mono-facial solar modules (labelled A to I) are subjected to different magnitudes of forward bias (voltage) and for different time periods, as shown in Tables 1 and 2, below. The operational performance characteristics of the nine solar modules A to I  
15 are tested prior to the modules being subjected to the passivation methods 200. These ‘Initial’ performance tests determined the pre-passivation photovoltaic performance characteristics of each module 10 (e.g., the current-voltage characteristics) under illuminated conditions. After the preliminary performance test, each solar module 10 is subjected to a different passivation method 200 comprising different values of the controllable variables (as identified in the  
20 ‘Applied Current’ and ‘Duration’ columns shown in Tables 1 and 2 below). After the passivation methods 200 are completed, the solar modules A to I are then subjected to ‘Final’ performance test to determine their respective post-passivation photovoltaic performance characteristics.

For this experiment, at least some of the solar modules 10 are subjected to different voltages  
25 (forward biases) to induce different forward currents in the solar module. For example, a current of 10A (e.g. +10A) is induced in solar module A, whereas a current of 33A (e.g. +33A) is induced in solar modules B to G, and each of solar modules H and I are subjected to a current of 44A (e.g. +44A). Some of the solar modules experienced the same level of voltage but for different time periods. For example, each of solar modules B to G are supplied with a  
30 current of 33 A, but with the duration of the treatment increasing from around 15 mins (B) to 120 mins (G).

The effect of the different passivation methods on the performance characteristics of solar modules A to I is shown in Tables 1 and 2, below. Specifically, Table 1 describes the changes  
35 in Fill Factor and open circuit voltage, whereas Table 2 describes the change in power at the

maximum power point (MPP). The results of Experiment A are also shown graphically in Figs. 6 to 8.

Table 1 – Experiment A - Fill Factor and Open Circuit Voltage

| Module | Applied Current (A) | Duration (min) | Fill Factor (FF) |           |           | Open Circuit Voltage (Voc) |           |           |
|--------|---------------------|----------------|------------------|-----------|-----------|----------------------------|-----------|-----------|
|        |                     |                | Initial (%)      | Final (%) | Diff. (%) | Initial (V)                | Final (V) | Diff. (V) |
| A      | 10A                 | 60 min         | 79.58            | 79.59     | 0.01      | 44.380                     | 44.40     | 0.023     |
| B      | 33A                 | 15 min         | 79.35            | 79.58     | 0.23      | 44.32                      | 44.35     | 0.030     |
| C      | 33A                 | 30 min         | 79.33            | 79.70     | 0.37      | 44.33                      | 44.38     | 0.053     |
| D      | 33A                 | 30 min         | 79.26            | 79.62     | 0.41      | 44.32                      | 44.38     | 0.055     |
| E      | 33A                 | 60 min         | 79.14            | 79.68     | 0.53      | 44.35                      | 44.42     | 0.065     |
| F      | 33A                 | 60 min         | 79.11            | 79.78     | 0.66      | 44.31                      | 44.40     | 0.093     |
| G      | 33A                 | 120 min        | 79.65            | 80.43     | 0.78      | 44.42                      | 44.48     | 0.063     |
| H      | 44A                 | 30 min         | 79.24            | 79.61     | 0.37      | 44.11                      | 44.13     | 0.020     |
| I      | 44A                 | 30 min         | 79.37            | 79.95     | 0.58      | 44.11                      | 44.14     | 0.030     |

5

Considering the results shown in Table 2, the largest difference in power at the MPP is observed for solar modules D to G, which are passivated with a current of 33A for at least 30 mins. The largest absolute increase in power at the MPP is achieved for solar module F. However, the largest percentage increase in fill factor is observed from solar module G (summarised in Table 3, below) which is passivated with a current of 33A for 120 mins.

10

Table 2 – Experiment A - Maximum Power Point (MPP)

| Module | Applied current (A) | Duration (min) | Initial power (W) | Final power(W) | Difference (W) | Gain (%) |
|--------|---------------------|----------------|-------------------|----------------|----------------|----------|
| A      | 10A                 | 60 min         | 370.80            | 371.87         | 1.070          | 0.29%    |
| B      | 33A                 | 15 min         | 368.83            | 370.10         | 1.270          | 0.34%    |
| C      | 33A                 | 30 min         | 371.05            | 372.83         | 1.783          | 0.48%    |
| D      | 33A                 | 30 min         | 369.60            | 372.25         | 2.650          | 0.72%    |
| E      | 33A                 | 60 min         | 370.10            | 372.55         | 2.450          | 0.66%    |
| F      | 33A                 | 60 min         | 369.13            | 372.60         | 3.467          | 0.94%    |
| G      | 33A                 | 120 min        | 371.90            | 374.85         | 2.950          | 0.79%    |
| H      | 44A                 | 30 min         | 359.68            | 361.11         | 1.430          | 0.40%    |

|   |     |        |        |        |       |       |
|---|-----|--------|--------|--------|-------|-------|
| I | 44A | 30 min | 360.20 | 362.00 | 1.800 | 0.50% |
|---|-----|--------|--------|--------|-------|-------|

Each of the solar modules A to I has a  $I_{mpp}$  of around 10 Amperes a short circuit current of around 10.5 Amperes, and an overload current of 25 Amperes. Each of the highest performing solar modules D to G are passivated with a current that exceeds the module's short circuit current and overload current. However, an increase in the power at the MPP value is also observed in solar module A, which is passivated with a current of around 10 A which is lower than the overload current and substantially equal to the  $I_{mpp}$ . Furthermore, it is noted that increasing the current does not necessarily result in further increases in power at MPP. For example, solar modules H and I (44A, 30 min) achieve similar increases in power at the MPP to solar module C, which is passivated for a similar time period (30 min) but with a significantly lower current (33A).

A further experiment comprised a solar module which is passivated with a current of 70A for a period of 10 mins, which resulted in an increase in the power at the MPP of 1.4W. A similar increase in power at the MPP is achieved with module B, which is passivated with a current of 33A for 15 min. Thus, the increasing current (e.g. 70A) is considered not to be beneficial to the passivation of the solar modules per se, but reduces the amount of time that the passivation method is executed for.

Table 3 – Experiment A – Optimum Passivation

| Module               | Power at MPP (W) | Short Circuit Current (A) | Open Circuit Voltage (Voc) | Fill Factor (%) |
|----------------------|------------------|---------------------------|----------------------------|-----------------|
| Initial              | 371.90           | 10.51                     | 44.42                      | 79.65           |
| Final – 33A, 120 min | 374.85           | 10.48                     | 44.48                      | 80.43           |
| Gain                 | 2.95             | -0.03                     | 0.06                       | 0.78            |
| Initial              | 369.1            | 10.5                      | 44.3                       | 79.1            |
| Final – 33A, 60 min  | 372.60           | 10.52                     | 44.40                      | 79.78           |
| Gain                 | 3.47             | -0.01                     | 0.09                       | 0.66            |

Similar experiments are carried out on three solar modules in which the passivation method comprised injecting a current of 33A into the modules for 30 seconds, 2 mins and 5 mins, respectively. Further experiments are conducted in which two solar modules are passivated with a current of 50A for 30 seconds and 2 mins, respectively. Also, experiments are carried out in which a solar module is passivated with a current of 70A for 5 mins. In each of these

experiments, no change in the MPP is observed in the results for the pre-passivation and post-passivation performance testing.

Table 4 shows the effect that injecting current into the solar modules has on the temperature of the solar module, over time. The results are also shown graphically in Fig. 9. These results corresponding to modules C, D, E and G indicate that the temperatures of the solar modules increases over time for a constant injected current (33A). Furthermore, comparing the performance results of solar modules D and I indicates that the temperatures of the solar cells increase with increasing injected current (e.g., from 33A to 44A, respectively) for a similar passivation period.

Table 4 – Experiment A - Temperature

| Module | Time (min) | Temp. (°C) |
|--------|------------|------------|
| C      | 15 min     | 80         |
| D      | 30 min     | 83         |
| E      | 60 min     | 93         |
| G      | 120 min    | 110        |
| I      | 30 min     | 95         |

The relationship between the applied voltage and the temperature of the solar module will be further discussed with reference to Table 5, below, and Fig. 10. In this second Experiment B, a solar module is passivated with a current of 33A for a period of 60 mins. The current is maintained at a constant value (33A) whilst the voltage required to maintain the current is measured every 5 minutes. Also, the temperature is measured at the same 5-minute intervals.

Table 5 – Experiment B - Voltage vs. Temperature

| Time (min) | Temp. (°C) | Voltage (V) | Time (min) | Temp. (°C) | Voltage (V) |
|------------|------------|-------------|------------|------------|-------------|
| 0 min      | 29.0       | 52.3        | 35 min     | 74.0       | 46.70       |
| 5 min      | 49.9       | 49.58       | 40 min     | 75.4       | 46.67       |
| 10 min     | 60.4       | 48.37       | 45 min     | 76.2       | 46.60       |
| 15 min     | 65.5       | 47.74       | 50 min     | 76.8       | 46.54       |
| 20 min     | 68.9       | 47.30       | 55 min     | 77.4       | 46.46       |
| 25 min     | 71.5       | 47.09       | 60 min     | 78.0       | 46.40       |
| 30 min     | 72.5       | 46.90       |            |            |             |

The passivation voltage required to achieve the constant current (33A) decreases over time, as the temperature increases. Specifically, as the time and temperature increase the voltage slowly drops and then stabilises. This is due to the decrease in resistance of the solar module as the temperature increases due to the flow of current.

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It will be appreciated that the voltage required to achieve a given current (e.g., 33A) is dependent on the resistance associated with the plurality of solar cells 12 connected together within the solar module 10 (e.g., the type and number of solar cells). For example, a larger number of solar cells (e.g., 66 or 72 solar cells) would exhibit a larger resistance than the fifty-four solar cells 12 installed within the module 10 shown in Fig. 1. A greater electrical resistance would require a larger voltage (e.g., passivation voltage) to achieve the same current value.

According to an exemplary arrangement the solar module 10 is manufactured by laminating the plurality of solar cells 12 within the outer casing 14 of the module 10. Such manufacturing methods typically involve sandwiching the plurality of solar cells 12 (and the encapsulant layers 20a, 20b) between the front and back sheets 24a, 24b, before applying heat and pressure to bond the solar module 10 together. According to an exemplary passivation method 200 of the present invention, the voltage is only applied to the solar module 10 once the heat from the manufacturing process has at least partially dissipated from the plurality of solar cells 12.

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For example, the passivation method 200 may involve only proceeding with method step 206 in dependence on the temperature of the plurality of solar cells 12 being below a pre-determined temperature (e.g., room temperature, around 25°C). In this exemplary method, the method step 206 includes monitoring the temperature of the solar cells 12 within the solar module 10. For example, the temperature of the solar cells 12 may be directly measured with an infrared thermometer. Then, only when the measured temperature of the solar cells 12 drops below the pre-determined temperature does the passivation method proceed.

It is noted that each of the solar modules A to I from Experiment A are allowed to cool to around room temperature before the passivation method 200 is applied. In a further exemplary Experiment C, a solar module 10 is passivated according to the present method 200, but in this case the method involved connecting the solar cells 12 to the passivation system 100 immediately following the lamination process, and a voltage is subsequently applied whilst the solar cells are still at an elevated temperature. Specifically, the solar module is passivated with a current of 33A for a period of 30 mins, which is equivalent to solar modules C and D from

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Experiment A. However, unlike solar modules C and D from Experiment A, the solar module from Experiment C resulted in substantially no increase in the MPP of the solar module.

5 In another aspect of Experiment C, a further solar module is passivated with a current of 33A for a period of 15 mins, which is equivalent to solar module B from Experiment A. In this case, the 'hot laminated' and passivated solar module exhibited an increase in MPP of 0.9 W. However, this is still lower than the corresponding increase in MPP of 1.2W which is achieved with an equivalent 'cold' solar module B from Experiment A. The present applicants have discovered that the method according to the present invention is able to achieve increased  
10 passivation of a plurality of solar cells within a solar module when the solar cells are not being heated by an external source, or are not still at an elevated temperature following a method of manufacturing the solar module.

In the drawings, the thickness of sheets, layers, films, etc., are exaggerated for clarity.  
15 Furthermore, it will be understood that when an element such as a layer, film, region, or substrate is referred to as being "on" another element, it can be directly on the other element or intervening elements may also be present. In contrast, when an element is referred to as being "directly on" another element, there are no intervening elements present.

## CLAIMS

1. A method of passivating a plurality of solar cells arranged within an at least partially manufactured solar module, wherein the solar module comprises a plurality of solar cells and  
5 an electrical assembly that connects the plurality of solar cells together into one or more strings of solar cells, wherein the electrical assembly is connectable to an electrical circuit which is external to the solar module, wherein the method comprises:
- connecting the electrical assembly to an external electrical circuit that comprises a current supplier; and  
10 supplying a forward current to the plurality of solar cells using the current supplier; and wherein the step of supplying the forward current is conducted before lamination of the solar module or after lamination of the solar module.
2. The method according to claim 1, wherein the at least partially manufactured solar  
15 module comprises the plurality of solar cells arranged within an outer casing of the solar module.
3. The method according to claim 2, wherein the outer casing of the at least partially manufactured solar module comprises a front sheet and a back sheet, wherein the at least  
20 partially manufactured solar module comprises an encapsulant which is interposed with the plurality of solar cells between the front and back sheets and heated to bond the solar cells to the outer casing to form the at least partially manufactured solar module; wherein:
- the step of supplying the forward current is conducted after lamination of the solar module; and  
25 the method further comprises allowing the heat from the at least partially manufactured solar module to at least partially dissipate from the plurality of solar cells before supplying forward current to the plurality of solar cells.
4. The method according to any one of the preceding claims, wherein the method  
30 comprises supplying forward current to the plurality of solar cells in dependence on the temperature of the plurality of solar cells being at or below a pre-determined temperature.
5. The method according to claim 4, wherein the pre-determined temperature is room temperature, optionally 20°C.

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6. The method according to any one of the preceding claims, wherein the magnitude of the forward current supplied to the plurality of solar cells is greater than or equal to the magnitude of a nominal power current of at least one of the solar cells.
- 5 7. The method according to claim 6, wherein the forward current supplied to the plurality of solar cells is at least 12 A.
8. The method according to claim 6 or claim 7, wherein the magnitude of the forward current supplied to the plurality of solar cells is greater than or equal to the magnitude of a short circuit current of at least one of the solar cells.
- 10 9. The method according to any of claims 6 to 8, wherein the magnitude of the forward current supplied to the plurality of solar cells is greater than the magnitude of a nominal power current of the solar module.
- 15 10. The method according to claim 9, wherein the magnitude of the forward current supplied to the plurality of solar cells is greater than or equal to the magnitude of a short circuit current of the solar module.
- 20 11. The method according to claim 10, wherein the method comprises supplying a forward current to the plurality of solar cells which is at least 314% of the short circuit current of the solar module.
- 25 12. The method according to any one of the preceding claims, wherein the method comprises supplying forward current to the plurality of solar cells for at least 30 seconds, optionally for at least 1 minute, further optionally for at least 120 minutes.
- 30 13. The method according to any one of the preceding claims, wherein:  
the current supplier comprises a voltage source; and  
the step of supplying the forward current comprises configuring the voltage source to apply a forward voltage to the electrical assembly to thereby supply the forward current to the plurality of solar cells using the voltage source.
- 35 14. The method according to any one of the preceding claims, wherein the forward current is applied to the plurality of solar cells when the solar module is under dark conditions.

15. The method according to any one of the preceding claims, wherein each of the plurality of solar cells comprises a crystalline silicon substrate.
16. The method according to any one of the preceding claims, wherein one or more of the plurality of solar cells is a heterojunction technology (HJT) solar cell.
17. A method of at least partially manufacturing a solar module, wherein the method comprises:
- connecting a plurality of solar cells into one or more strings of solar cells using an electrical assembly which is connectable to an electrical circuit that is external to the solar module; and
- passivating the plurality of solar cells arranged within the at least partially manufactured solar module according to any one of claims 1 to 16.
18. The method according to claim 17, wherein:
- the method further comprises laminating the solar module; and
- the step of supplying the forward current as part of passivating the plurality of solar cells is conducted before or after the step of laminating the solar module.
19. The method according to claim 17 or 18, wherein the method further comprises arranging the plurality of solar cells within an outer casing of the solar module.
20. The method according to claim 19, wherein the outer casing comprises a front sheet and a back sheet, wherein the method of at least partially manufacturing the solar module further comprises;
- interposing an encapsulant of the solar module and the plurality of solar cells between the front sheet and back sheet of the outer casing; and
- heating the encapsulant to bond the solar cells within the outer casing;
- wherein:
- the step of supplying the forward current as part of passivating the plurality of solar cells is conducted after laminating the solar module; and
- the step of passivating the plurality of solar cells further comprises allowing the heat from the heating of the encapsulant to at least partially dissipate from the plurality of solar cells before supplying forward current to the plurality of solar cells.