

SOLAR CELL AND METHOD OF MANUFACTURING A SOLAR CELL

FIELD OF THE DISCLOSURE

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The present disclosure relates to a solar cell and a method of manufacturing the solar cell.

BACKGROUND

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A typical solar module for providing electrical energy from sunlight comprises an array of solar cells, each comprising a photovoltaic element, or substrate.

A general aim for solar cell development is to attain high conversion efficiency balanced by a need for reduced production costs. Recent efforts to achieve this have focussed on tunnel-interdigitated back contact solar cells (tunnel-IBC cells) that place both contacts on the back surface of the solar cells, in order to reduce blocking of incident light on the front surface of the solar cells. This type of cell also requires less sophisticated patterning techniques than conventional IBC cells by the use of tunnelling concepts.

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WO2021018517A1 proposes a tunnel-IBC cell structure where only one polarity (e.g. the positively-doped elements or the negatively-doped elements) in the back contact structure is patterned, and both the electron and hole collectors comprise nano-crystalline silicon to reduce contact resistance. However, in order to reduce leakage current in the cell, the patterned portion of the structure comprises multiple layers of differing cross-sections in planes parallel to the plane of a back surface of the solar cell. Producing these patterned layers having different cross-sections either requires the fabrication process to use multiple masks, or to hover the mask over the substrate during deposition of one or more of said layers.

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Thus, further improvements in such tunnel-interdigitated back contact solar cells are desired in order to reduce hole and electron contact resistance, reduce leakage current between adjacent contacts, and further simplify manufacturing techniques.

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35 SUMMARY

In general, the present disclosure provides a solar cell comprising: a substrate having a back surface; a passivation layer arranged on the back surface of the substrate, the passivation layer comprising a back surface; and an interdigitated back contact, the interdigitated back contact comprising a first charge-carrier collector arranged on the back surface of the passivation layer and interdigitated with a

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second charge-carrier collector arranged on the back surface of the passivation layer. The first charge-carrier collector comprises a plurality of first doped elements arranged on the back surface of the passivation layer, the first doped elements having a first conductivity type; and a plurality of second doped elements arranged on the first doped elements, the second doped elements having a second conductivity type that is opposite the first conductivity type. The second charge-carrier collector comprises a plurality of third doped elements arranged on the back surface of the passivation layer, the third doped elements having the second conductivity type.

In a first aspect, in the above-described solar cell of the present disclosure, the third doped elements are more crystalline than the first doped elements and/or the second doped elements.

In some examples, the substrate may be a crystalline substrate, such as a crystalline silicon-based wafer. The front and/or back surface of the substrate may be textured.

In some examples, the first doped elements may comprise silicon (e.g. may be first doped silicon elements). In some examples, the second doped elements may comprise silicon (e.g. may be second doped silicon elements). In some examples, the third doped elements may comprise silicon (e.g. may be third doped silicon elements).

In some examples, the difference in the crystalline percentage of the third doped elements and the crystalline percentage of the second doped elements may be greater than or equal to 5%.

In some examples, the difference in the crystalline percentage of the third doped elements and the crystalline percentage of the first doped elements may be greater than or equal to 10%.

Accordingly, the third doped elements are arranged on the passivation layer in between the first charge-carrier collectors (e.g. between the first doped elements and/or the second doped elements). By the third doped elements being more crystalline than the second doped elements and/or being more crystalline than the first doped elements, the shunt resistance between the first charge-carrier collector and second charge-carrier collector is greater than if the third doped elements had the same crystallinity as the first and/or second doped elements. By increasing said shunt resistance, a leakage current from the first charge-carrier collector to the second charge-carrier collector can be reduced. By reducing the leakage current, the current across the tunnel junction provided between the first doped element and a second doped element can be increased, thereby increasing the fill factor, current density, open-circuit voltage and efficiency of the solar cell.

In some examples, the third doped elements being more crystalline than the first doped elements and/or the second doped elements may be defined as the average (e.g. mean) crystallinity of the third doped elements being greater than the average (e.g. mean) crystallinity of the first doped elements and/or the second doped elements. Alternatively, the third doped elements being more crystalline than the first

doped elements and/or the second doped elements may be defined as the crystallinity of a layer of maximum crystallinity in the third doped elements being greater than the crystallinity of a layer of maximum crystallinity of the first doped elements and/or the second doped elements.

- 5 The crystallinity may be defined as the proportion (e.g. expressed as a fraction or percentage) of an element, by mass or volume, that is in the crystalline phase. In some examples, the crystallinity (i.e. crystalline fraction or percentage) of a given element may be measured using Raman spectroscopy (i.e. the crystallinity may be the Raman crystallinity). The method of measuring the crystallinity using Raman spectroscopy may comprise the method set out in C. Droz et al.: Relationship between Raman
- 10 crystallinity and open-circuit voltage in micro-crystalline silicon solar cells, Solar Energy Materials & Solar Cells 81 (1), 61-71, 2004). The Raman crystallinity, X_c , may be defined as:

$$X_c = \frac{I_{510} + I_{520}}{I_{480} + I_{510} + I_{520}}$$

- 15 Where I_{480} , I_{510} , and I_{520} are the integrated areas below a gaussian peak at 480 cm⁻¹, 510 cm⁻¹, and 520 cm⁻¹, respectively. A micro-crystalline or nano-crystalline silicon element may be defined as an element with $X_c > 5\%$, whilst an amorphous silicon element may be defined as an element with $X_c \leq 5\%$.
- 20 In some examples, the difference in the crystalline percentage of the third doped elements and the crystalline percentage of the second doped elements may be greater than or equal to 5%, greater than or equal to 7%, greater than or equal to 10%, greater than or equal to 12%, greater than or equal to 15%, greater than or equal to 16%, greater than or equal to 17%, greater than or equal to 18%, greater than or equal to 19%, greater than or equal to 20%, greater than or equal to 21%, greater than or equal to 22%, greater than or equal to 23%, greater than or equal to 24%, greater than or equal to 25%, greater than or equal to 26%, greater than or equal to 27%, greater than or equal to 28%, greater than or equal to 29%, or greater than or equal to 30%.

- 30 In some examples, the difference in the crystalline percentage of the third doped elements and the crystalline percentage of the second doped elements may be less than or equal to 12%, less than or equal to 15%, less than or equal to 16%, less than or equal to 17%, less than or equal to 18%, less than or equal to 19%, less than or equal to 20%, less than or equal to 21%, less than or equal to 22%, less than or equal to 23%, less than or equal to 24%, less than or equal to 25%, less than or equal to 26%, less than or equal to 27%, less than or equal to 28%, less than or equal to 29%, or less than or equal to 30%.
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In some examples, the difference in the crystalline percentage of the third doped elements and the crystalline percentage of the first doped elements may be greater than or equal to 10%, greater than or equal to 12%, greater than or equal to 15%, greater than or equal to 16%, greater than or equal to 17%,

greater than or equal to 18%, greater than or equal to 19%, greater than or equal to 20%, greater than or equal to 21%, greater than or equal to 22%, greater than or equal to 23%, greater than or equal to 24%, greater than or equal to 25%, greater than or equal to 26%, greater than or equal to 27%, greater than or equal to 28%, greater than or equal to 29%, or greater than or equal to 30%.

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In some examples, the difference in the crystalline percentage of the third doped elements and the crystalline percentage of the first doped elements may be less than or equal to 10%, less than or equal to 12%, less than or equal to 15%, less than or equal to 16%, less than or equal to 17%, less than or equal to 18%, less than or equal to 19%, less than or equal to 20%, less than or equal to 21%, less than or equal to 22%, less than or equal to 23%, less than or equal to 24%, less than or equal to 25%, less than or equal to 26%, less than or equal to 27%, less than or equal to 28%, less than or equal to 29%, or less than or equal to 30%.

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In some examples, the crystalline percentage of the first doped elements may be greater than or equal to 35%. By way of example, the crystalline percentage of the first doped elements may be greater than or equal to 40%, greater than or equal to 41%, greater than or equal to 42%, greater than or equal to 43%, greater than or equal to 44%, or greater than or equal to 45%. In some examples, the crystalline percentage of the first doped elements may be less than or equal to 50%. By way of example, the crystalline percentage of the first doped elements may be less than or equal to 45%. less than or equal to 44%, less than or equal to 43%, less than or equal to 42%, less than or equal to 41%, or less than or equal to 40%.

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In some examples, the crystalline percentage of the second doped elements may be greater than or equal to 35%. By way of example, the crystalline percentage of the first doped elements may be greater than or equal to 40%, greater than or equal to 41%, greater than or equal to 42%, greater than or equal to 43%, greater than or equal to 44%, greater than or equal to 45%, greater than or equal to 46%, greater than or equal to 47%, greater than or equal to 48%, greater than or equal to 49%, or greater than or equal to 50%. In some examples, the crystalline percentage of the first doped elements may be less than or equal to 55%. By way of example, the crystalline percentage of the first doped elements may be less than or equal to 50%. less than or equal to 49%, less than or equal to 48%. less than or equal to 47%, less than or equal to 46%, less than or equal to 45%, less than or equal to 44%, less than or equal to 43%, less than or equal to 42%, less than or equal to 41%, or less than or equal to 40%.

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In some examples, the crystalline percentage of the third doped elements may be greater than or equal to 50%. By way of example, the crystalline percentage of the first doped elements may be greater than or equal to 55%, greater than or equal to 56%, greater than or equal to 57%, greater than or equal to 58%, greater than or equal to 59%, greater than or equal to 60%, greater than or equal to 61%, greater than or equal to 62%, greater than or equal to 63%, greater than or equal to 64%, or greater than or equal to 65%. In some examples, the crystalline percentage of the second doped elements may be less

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than or equal to 70%. By way of example, the crystalline percentage of the first doped elements may be less than or equal to 65%, less than or equal to 64%, less than or equal to 63%, less than or equal to 62%, less than or equal to 60%, less than or equal to 59%, less than or equal to 58%, less than or equal to 57%, less than or equal to 56%, or less than or equal to 55%.

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In a second aspect, in the above-described solar cell of the present disclosure, the first charge-carrier collector may further comprise an oxide layer arranged on (e.g. arranged directly on) the first doped elements; and the plurality of second doped elements may be arranged on (e.g. arranged directly on) the oxide layer. That is, the first charge-carrier collector further comprises an oxide layer arranged on (e.g. arranged directly on) each of the first doped elements; and each of the plurality of second doped elements is arranged on (e.g. arranged directly on) a respective one of the oxide layers such that each oxide layer is interposed between a respective pair of first and second doped elements. That is, the solar cell may be a TOPCon (Tunnel oxide passivated contact) IBC solar cell (e.g. an n-type TOPCon IBC solar cell where the oxide layer is provided within the electron collector).

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Each stack of a first doped element, the oxide layer and a second doped element provides a tunnel junction in the first-charge carrier collector. Portions of the oxide layer adjacent the second charge-carrier collector may be interposed between the first doped element and the third doped element. The oxide layer can act to decrease the resistance of the tunnel junction in the first charge-carrier collector compared to if the oxide layer was not present in the first charge-carrier collector and/or increase the shunt resistance between the first charge-carrier collector and second charge-carrier collector. In this way, a leakage current from the first doped elements into the third doped elements (e.g. via the second doped element, or directly between the first doped elements and third doped elements) can be reduced and/or the current through the tunnel junction can be increased, thereby increasing the fill factor, current density, open-circuit voltage and efficiency of the solar cell.

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The solar cell according to the first aspect may also further comprise an oxide layer arranged on the first doped elements and interposed between the first doped elements and the second doped elements.

A tunnel junction is provided between the first doped elements and the second doped elements. By interposing an oxide layer in this manner, the resistance of the tunnel junction can be reduced, thereby increasing the charge-carrier current through the first charge-carrier collector and thus increasing the fill factor and solar cell efficiency.

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The oxide layer may be understood to be a layer that reduces the resistance to tunnelling across a tunnel junction (i.e. enhances tunnelling within the charge-carrier collector). The oxide layer may be a metal oxide or metalloid oxide layer. The tunnelling layer may be (e.g. comprise, or consist of) a SiO_x layer, a Ta_2O_5 layer, an Al_2O_3 layer or an HfO_2 layer. An SiO_x layer may be defined as a layer comprising, or consisting, of silicon monoxide (SiO) and/or one or more of its suboxides (e.g. SiO_2 , SiO_3^{2-} , SiO_4^{4-}).

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In some examples, the oxide layer on each first doped element may comprise a first portion positioned for a tunnelling current through the first charge-carrier collector to flow through and a second portion positioned for a leakage current between the first charge-carrier collector and second charge-carrier collector to flow through. The second portion of the oxide layer may be thicker than the first portion of the oxide layer. That is, the oxide layer on each first doped element comprises a first portion interposed between the first and second doped elements (e.g. at a central position on the first doped element) and a second portion interposed between a first doped element and the second charge-carrier collector (e.g. at a side of the first doped element), the oxide layer thickness being greater in second portion than the first portion. By way of further example, the thickness of the oxide layer may decrease with increasing distance from the back surface of the passivation layer. By the oxide layer being thicker at positions on each first doped element adjacent the second charge-carrier collector than at a central position on each first doped element, the oxide layer can act to simultaneously increase the shunt resistance between the first charge-carrier collector and second charge-carrier collector (i.e. where the oxide layer is thicker) and decrease the resistance of the tunnel junction in the first charge-carrier collector (i.e. where the oxide layer is thinner). In this way, a leakage current from the first doped elements into the third doped elements can be reduced and the current through the tunnel junction can be increased, thereby increasing the fill factor, current density, open-circuit voltage and efficiency of the solar cell.

The thickness of a given layer or region/portion thereof (e.g. the thickness of the oxide layer at different positions on the first doped element) may be defined as the dimension of the layer or region/portion thereof in a direction that is (substantially) perpendicular to the back surface of an underlying layer (e.g. perpendicular to the back surface of the crystalline silicon-based wafer, the back surface of the passivation layer, or a back surface of the first doped element) at a position on that underlying layer.

The passivation layer may be an intrinsic layer. The passivation layer may be an amorphous layer, e.g. an amorphous silicon layer or hydrogenated amorphous silicon layer. The passivation layer may be an intrinsic amorphous layer, e.g. an intrinsic hydrogenated amorphous silicon layer (a-Si:H(i)).

The first doped elements may have n-type conductivity (i.e. be n-type doped) and the second and third doped elements may have p-type conductivity (i.e. be p-type doped). Alternatively, the first doped elements may have p-type conductivity (i.e. be p-type doped) and the second doped silicon layer may have n-type conductivity (i.e. be n-type doped).

The first doped elements may be nano-crystalline or micro-crystalline. The first doped elements may comprise, or consist of, nano-crystalline (hydrogenated) silicon. The first doped elements may not comprise an amorphous (hydrogenated) silicon layer or be an amorphous (hydrogenated) silicon element.

A nano-crystalline silicon element may be defined as an element containing nanometre-sized silicon crystals within a matrix comprising hydrogenated amorphous silicon. Similarly, a micro-crystalline

silicon element may be defined as an element containing micrometre-sized silicon crystals within a matrix comprising hydrogenated amorphous silicon. Nanometre-sized crystals may be defined as crystals having a maximum dimension greater than equal to a nanometre. Nanometre-sized crystals may be defined as crystals having a maximum dimension less than one micrometre. Micrometre-sized
5 crystals may be defined as having a maximum dimension greater than or equal to a micrometre. Micrometre-sized crystals may be defined as having a maximum dimension less than one millimetre.

In some examples, the plurality of first doped elements may be spaced apart from each other in a lengthwise direction of the solar cell. Each first doped element may have an elongate cross section in
10 a plane parallel to the back surface of the passivation layer. By way of example, each first doped element may have a width direction extending in the lengthwise direction of the solar cell and a length direction extending in the width wise direction of the solar cell, and the length of the first doped element may be greater than the width of the first doped element. Each first doped element may extend substantially all the way across the width of the solar cell. The first doped elements may be equally
15 spaced apart along the lengthwise direction of the solar cell by apertures. The apertures may also be elongate and have a length direction extending in the width wise direction of the solar cell.

The first doped element may be directly arranged on the back surface of the passivation layer. In such a case, the portion of the first doped element that abuts the back surface of the passivation layer may
20 be nano-crystalline or micro-crystalline, as opposed to amorphous (e.g. comprising no crystalline regions).

The crystalline percentage of the first doped element may increase continuously with increasing distance from the surface of the first doped element adjacent the passivation layer (i.e. there may be
25 no discontinuities in the change in crystalline percentage with increasing distance from the passivation layer, e.g. no step changes in the crystalline percentage and/or the rate of change of crystalline percentage with distance from the surface adjacent the passivation layer).

In examples where the first doped elements are first doped silicon elements and the oxide layer is an
30 SiO_x layer, the SiO_x layer may be formed by applying a carbon dioxide plasma treatment to the first doped silicon elements. In some examples, the carbon dioxide plasma treatment may be applied to the first doped silicon elements through a mask. In some examples, the mask may be such that the carbon dioxide plasma treatment is only applied to the first doped silicon elements, e.g. the carbon dioxide plasma treatment may not be applied to the regions of the passivation layer that are exposed between
35 the first doped silicon elements before the third doped silicon elements are arranged thereon. Carbon dioxide plasma treatment may comprise exposing the surface to have carbon dioxide plasma treatment applied to it to a plasma comprising carbon dioxide molecules (i.e. CO_2) and plasma species derived therefrom (e.g. CO^+ , e^- , O^+ , C^+ , CO^+ , C_2 , O_2), for example, the carbon dioxide plasma may consist of carbon dioxide molecules and plasma species derived therefrom. The plasma to be used for carbon
40 dioxide plasma treatment may not comprise silane, silanide, silylene, or other silicon-based gas species

or plasma species derived therefrom. The carbon dioxide plasma treatment may be configured not to deposit additional silicon atoms onto the surface being treated.

5 In some examples, the thickness of the first portion of the SiO_x layer may be less than 2.0 nm. In some examples, the thickness of the second portion of the SiO_x layer may be greater than or equal to 2.0 nm.

10 In some examples, the thickness of the first portion of the SiO_x layer may be less than or equal to 2.5 nm, less than or equal to 2.4 nm, less than or equal to 2.3 nm, less than or equal to 2.2 nm, less than or equal to 2.1 nm, less than or equal to 2.0 nm, less than or equal to 1.9 nm, less than or equal to 1.8 nm, less than or equal to 1.7 nm, less than or equal to 1.6 nm, less than or equal to 1.5 nm, less than or equal to 1.4 nm, less than or equal to 1.3 nm, less than or equal to 1.2 nm, less than or equal to 1.1 nm, or less than or equal to 1.0 nm. The thickness of the first portion of the SiO_x layer may be greater than or equal to 0.1 nm, greater than or equal to 0.2 nm, greater than or equal to 0.3 nm, greater than or equal to 0.2 nm, greater than or equal to 0.3 nm, greater than or equal to 0.4 nm, greater than or equal to 0.5 nm, greater than or equal to 0.6 nm, greater than or equal to 0.7 nm, greater than or equal to 0.8 nm, greater than or equal to 0.9 nm, or greater than or equal to 1.0 nm.

20 In some examples, the thickness of the second portion of the SiO_x layer may be greater than or equal to 2.5 nm, greater than or equal to 2.4 nm, greater than or equal to 2.3 nm, greater than or equal to 2.2 nm, greater than or equal to 2.1 nm, greater than or equal to 2.0 nm, greater than or equal to 1.9 nm, greater than or equal to 1.8 nm, greater than or equal to 1.7 nm, greater than or equal to 1.6 nm, greater than or equal to 1.5 nm, greater than or equal to 1.4 nm, greater than or equal to 1.3 nm, greater than or equal to 1.2 nm, greater than or equal to 1.1 nm, or greater than or equal to 1.0 nm. The thickness of the second portion of the SiO_x layer may be less than or equal to 5.0 nm, less than or equal to 4.0 nm, less than or equal to 3.0 nm, or less than or equal to 2.5 nm.

30 In some examples, the passivation layer comprises hydrogenated amorphous silicon. The passivation layer may comprise a plurality of first regions having a first concentration of hydrogen atoms and a plurality of second regions having a second concentration of hydrogen atoms, the second concentration being lower than the first concentration. The first doped elements may be arranged on respective first regions of the passivation layer and the third doped elements may be arranged on respective second regions of the passivation layer. In this way, the third doped elements are arranged on the second regions of the passivation layer than have a high concentration of hydrogen atoms than the first regions of the passivation layer that the first doped elements are arranged on. Accordingly, the third doped elements may be more crystalline than the first doped elements. The first doped elements may be directly arranged on the first regions of the passivation layer. The third doped elements may be directly arranged on the second regions of the passivation layer. In this way, if the third doped elements have an interface with the first doped elements, the difference in crystallinity therebetween can provide a higher shunt resistance at such an interface compared to if their crystallinities were the same. The second regions of the passivation layer may have a higher concentration of hydrogen atoms than a

back surface of the first doped elements and/or the oxide layer (where present) arranged on the first doped elements. Accordingly, the third doped elements may be more crystalline than the second doped elements. The second doped elements may be directly arranged on the first doped elements or the oxide layer (where present). In this way, if the third doped elements have an interface with the second doped elements, the difference in crystallinity therebetween can provide a higher shunt resistance at such an interface compared to if their crystallinities were the same.

In some examples, the difference in hydrogen atom concentration between the first regions and second regions of the passivation layer may be provided by exposing the first regions and second regions to different hydrogen plasma treatments (e.g. different plasma powers, different pressures, different hydrogen flow rates, and different durations) and/or a different number of hydrogen plasma treatment steps. By way of example, the second regions of the passivation layer may have undergone a first hydrogen plasma treatment and a second hydrogen plasma treatment, whereas the first regions of the passivation layer may have only undergone the first hydrogen plasma treatment and/or the first doped elements and/or the oxide layer may have undergone only the second hydrogen plasma treatment. Hydrogen plasma treatment may comprise exposing the surface to have hydrogen plasma treatment applied to it to a plasma comprising hydrogen molecules (i.e. H_2) and plasma species derived therefrom (e.g. H^+ , e^- , H^-), for example, the hydrogen plasma may consist of hydrogen gas and plasma species derived therefrom. The plasma to be used for hydrogen plasma treatment may not comprise silane, silanide, silylene, or other silicon-based gas species or plasma species derived therefrom. The hydrogen plasma treatment may be configured not to deposit additional silicon atoms onto the surface being treated.

The first regions of the passivation layer may also, or alternatively, be differentiated from the second regions of the passivation layer by one or more of: the concentration of Si – H bonds in the second regions being higher than the concentration of Si – H bonds in the first regions; the concentration of Si – H_2 bonds in the second region being lower than the concentration of Si – H_2 bonds in the first region. The concentration of hydrogen atoms, the concentration of Si – H bonds and the concentration of Si – H_2 bonds may be measured using Fourier transform infrared (FTIR) spectroscopy as described in P. Gogoi, H.S. Jha, P. Agarwal, High band gap nanocrystallite embedded amorphous silicon prepared by hotwire chemical vapour deposition, Thin Solid Films 518 (2010) 6818–6828, <http://dx.doi.org/10.1016/j.tsf.2010.06.040>.

In some examples, the cross-sectional area of each first doped element in a plane parallel to the back surface of the passivation layer may decrease with increasing distance from the back surface of the passivation layer. In an embodiment, a cross-sectional shape of each first doped element is substantially dome shaped in a plane perpendicular to the length of the first doped element. In this way, a portion of each of the second doped elements may be interposed between the respective first doped element and the adjacent third doped elements. Accordingly, the shunt resistance of the solar cell can be increased by the third doped elements being more crystalline than the second doped elements and

consequently the leakage current between the first charge-carrier collector and the second charge-carrier collector can be reduced.

5 In some examples, the second doped elements and third doped elements may be formed as a single, continuous layer. That is, the second doped elements and third doped elements may not be arranged by separate deposition processes but rather a single deposition process where the second and third doped elements are grown/deposited simultaneously.

10 One or more of the passivation layer, the first doped elements, the second doped elements and the third doped elements may be deposited by plasma-enhanced chemical vapour deposition. Alternative deposition methods will be apparent to the person skilled in the art.

15 In general, the present disclosure provides a method of manufacturing a solar cell, said solar cell optionally implementing any one or more of the features disclosed herein. The method comprises the steps of: providing a substrate comprising a back surface; arranging a passivation layer on the back surface of the substrate, the passivation layer comprising a back surface; arranging an interdigitated back contact on the passivation layer, the interdigitated back contact comprising a first charge-carrier collector arranged on the back surface of the passivation layer and interdigitated with a second charge-carrier collector arranged on the back surface of the passivation layer, the step of arranging the
20 interdigitated back contact comprising: arranging a plurality of first doped elements of the first charge-carrier collector on first regions of the back surface of the passivation layer, the first doped elements having a first conductivity type; arranging a plurality of second doped elements of the first charge-carrier collector on the first doped elements, the second doped elements having a second conductivity type that is opposite the first conductivity type; and arranging a plurality of third doped elements of the second
25 charge-carrier collector on second regions of the back surface of the passivation layer, the third doped elements having the second conductivity type.

In a third aspect, in the above-described method of manufacturing a solar cell of the present disclosure, the method further comprises applying one or more hydrogen plasma treatments, the one or more
30 hydrogen plasma treatments being applied to the passivation layer and/or the first doped elements such that the crystalline fraction of the third doped elements is different to the crystalline fraction of the first doped elements and/or the second doped elements.

35 Application of a hydrogen plasma treatment to a surface can induce more crystalline growth in a material that is subsequently deposited on that treated surface than if no such hydrogen plasma treatment is applied to the surface. Accordingly, the application of one or more hydrogen plasma treatments to the solar cell during the manufacturing process can allow the crystalline fractions of elements to be manipulated. The claimed difference in crystalline fractions between the third doped elements and the first doped elements and/or the second doped elements results in the shunt resistance between the
40 first charge-carrier collector and second charge-carrier collector being greater than if these elements

had the same crystallinity. By increasing said shunt resistance, a leakage current from the first charge-carrier collector to the second charge-carrier collector can be reduced. By reducing the leakage current, the current across the tunnel junction provided between the first doped elements and second doped elements can be increased, thereby increasing the fill factor, current density, open-circuit voltage and efficiency of the solar cell.

In some examples, the step of applying one or more hydrogen plasma treatments to the solar cell may comprise applying a first hydrogen plasma treatment, the first hydrogen plasma treatment being applied to the passivation layer. The first hydrogen plasma treatment may be applied to the first regions and second regions of the passivation layer (i.e. the first hydrogen plasma treatment may be applied before the steps of arranging the plurality of first doped elements on first regions of the back surface of the passivation layer). That is, the first hydrogen plasma treatment may be applied to substantially all of the back surface of the passivation layer. Hydrogen plasma treatment may comprise exposing the surface to have hydrogen plasma treatment applied to it to a plasma comprising hydrogen molecules (i.e. H_2) and plasma species derived therefrom (e.g. H^+ , e^- , $H\cdot$), for example, the hydrogen plasma may consist of hydrogen molecules and plasma species derived therefrom. The plasma to be used for hydrogen plasma treatment may not comprise silane, silanide, silylene, or other silicon-based gas species or plasma species derived therefrom. The hydrogen plasma treatment may be configured not to deposit additional silicon atoms onto the surface being treated.

In some examples, where the method comprises applying the first hydrogen plasma treatment, the step of applying one or more hydrogen plasma treatments to the solar cell may further comprise applying a second hydrogen plasma treatment, the second hydrogen plasma treatment being applied to the second regions of the passivation layer. The second hydrogen plasma treatment may also be applied to the first doped elements or the oxide layer (where present). Rather than applying the second hydrogen plasma treatment, the first hydrogen plasma treatment may only be applied to the second regions of the passivation layer (i.e. and not to the first regions of the passivation layer, the first doped elements, and/or the oxide layer (where present)).

In examples where a first hydrogen plasma treatment is applied and a second hydrogen plasma treatment is applied, the second hydrogen plasma treatment may differ from the first hydrogen plasma treatment by one or more of: a flowrate of hydrogen gas being different, optionally higher, during the second hydrogen plasma treatment than during the first hydrogen plasma treatment; a chamber pressure being different, optionally higher, during the second hydrogen plasma treatment than during the first hydrogen plasma treatment; a plasma power being different, optionally higher, during the second hydrogen plasma treatment than during the first hydrogen plasma treatment; a plasma frequency being different, optionally higher, during the second hydrogen plasma treatment than during the first hydrogen plasma treatment; and a duration of the second hydrogen plasma treatment being different, optionally lower, than a duration of the first hydrogen plasma treatment. Alternatively, the first and second hydrogen plasma treatments may have the same parameters (e.g. said hydrogen plasma

treatments having the same flowrate of hydrogen gas, the same chamber pressure, the same plasma power, the same plasma frequency, and the same duration).

5 The process temperature during the first hydrogen plasma treatment and/or the second hydrogen plasma treatment may be approximately 200°C, for example greater than or equal to 180°C and/or less than or equal to 200°C. The flowrate of hydrogen gas during the first hydrogen plasma treatment may be approximately 1000 standard cubic centimetres per minute (SCCM), for example greater than or equal to 800 SCCM and/or less than or equal to 1200 SCCM. The flowrate of hydrogen gas during the second hydrogen plasma treatment may be approximately 9000 standard cubic centimetres per minute
10 (SCCM), for example greater than or equal to 8000 SCCM and/or less than or equal to 10000 SCCM. The chamber pressure during the first hydrogen plasma treatment may be approximately 80 Pascals, for example greater than or equal to 70 Pascals and/or less than or equal to 90 Pascals. The chamber pressure during the second hydrogen plasma treatment may be approximately 465 Pascals, for example greater than or equal to 420 Pascals and/or less than or equal to 500 Pascals. The plasma
15 power density (power per unit area of electrode) during the first hydrogen plasma treatment may be approximately 52 mW/cm², for example greater than or equal to 45 mW/cm² and/or less than or equal to 60 mW/cm². The plasma power during the second hydrogen plasma treatment may be approximately 73 mW/cm², for example greater than or equal to 65 mW/cm² and/or less than or equal to 81 mW/cm². The plasma frequency during the first hydrogen plasma treatment may be approximately 13.6 MHz.
20 The plasma frequency during the second hydrogen plasma treatment may be approximately 27.1 MHz. The duration of the first hydrogen plasma treatment may be approximately 15 second, for example greater than or equal to 13 seconds and/or less than or equal to 17 seconds. The duration of the second hydrogen plasma treatment may be approximately 10 seconds, for example greater than or equal to 8 seconds and/or less than or equal to 12 seconds.

25 In examples where the method comprises applying the first hydrogen plasma treatment, the steps of arranging the passivation layer on the back surface of the wafer and applying the first hydrogen plasma treatment may be conducted in the same deposition chamber as each other. In examples where the method comprises applying the second hydrogen plasma treatment, the steps of applying the second
30 hydrogen plasma treatment and arranging the second doped elements and/or arranging the third doped elements may be conducted in the same deposition chamber as each other. By conducting steps of the method in the same deposition chamber as each other, the number of instances of needing to move the partially-fabricated solar cell can be reduced, thereby simplifying the manufacturing process and reducing the manufacturing time compared to if movement between chambers is required, and reducing
35 the likelihood of damaging the partially-fabricated solar cell when moving it between chambers, thereby reducing the rejection rate of solar cells from the manufacturing process and reducing material wastage.

The method may further comprise the steps of applying a mask over the back surface of the passivation layer prior to the step of arranging the first doped elements. The method may further comprise removing
40 the mask after the step of arranging the first doped elements. The use of the mask in this way (i.e.

depositing the first doped elements through the mask) may provide the first doped elements with a patterned arrangement on the passivation layer and thus facilitate the interdigitating of the first charge-carrier collector and second charge-carrier collector within the interdigitated back contact. The step of applying the mask may be conducted after the step of applying the first hydrogen plasma treatment to the passivation layer. The step of removing the mask may be conducted before the step of applying the second hydrogen plasma treatment. The step of removing the mask may be conducted before the step of arranging the second doped elements and/or the step of arranging the third doped elements.

The method according to the third aspect, and in particular the first and second hydrogen plasma treatments, facilitates providing the first and second charge-carrier collectors such that the third doped elements are more crystalline than the second doped elements and/or are more crystalline than the first doped elements. This is because the second regions of the passivation layer undergo two hydrogen plasma treatments, which then induces more crystalline growth in the third doped elements in comparison to the surfaces that the second doped elements are deposited on, which undergo a single hydrogen plasma treatment. This difference in crystallinity results in the shunt resistance between the first charge-carrier collector and second charge-carrier collector being greater than if the third doped elements had the same crystalline fraction as the second doped elements and/or first doped elements. By increasing said shunt resistance, a leakage current from the first charge-carrier collector to the second charge-carrier collector can be reduced. By reducing the leakage current, the current across the tunnel junction provided between the first doped elements and the second doped elements can be increased, thereby increasing the fill factor, current density, open-circuit voltage and efficiency of the solar cell.

In some examples, the third doped elements may be more crystalline than the first doped elements and/or the second doped elements, for example, difference in the crystalline percentage of the third doped elements and the crystalline percentage of the second doped elements may be greater than or equal to 10%, the third doped elements having a higher crystalline percentage.

The method according to the third aspect may further comprise a step of applying a plasma treatment to the first doped silicon elements to form an oxide layer on the first doped elements. The second doped elements may then be arranged on the oxide layer. Where the first doped elements are first doped silicon elements, the plasma treatment may be a carbon dioxide plasma treatment to form a SiO_x layer on the first doped silicon elements. The second doped elements may then be arranged on the SiO_x layer. Carbon dioxide plasma treatment may comprise exposing the surface to have carbon dioxide plasma treatment applied to it to a plasma comprising carbon dioxide molecules (i.e. CO_2) and plasma species derived therefrom (e.g. CO^+ , e^- , $\text{O}^\cdot$, $\text{C}^\cdot$, $\text{CO}^\cdot$, C_2 , O_2), for example, the carbon dioxide plasma may consist of carbon dioxide molecules and plasma species derived therefrom. The plasma to be used for carbon dioxide plasma treatment may not comprise silane, silanide, silylene, or other silicon-based gas species or plasma species derived therefrom. The carbon dioxide plasma treatment may be configured not to deposit additional silicon atoms onto the surface being treated.

In a fourth aspect, in the above-described method of manufacturing a solar cell of the present disclosure, the method further comprises: applying a plasma treatment to the first doped elements to form an oxide layer on the first doped elements, the second doped elements then being arranged on
5 the oxide layer.

Each stack of a first doped element, the oxide layer, and a second doped element provides a tunnel junction in the first-charge carrier collector. Portions of the oxide layer on a first doped element that are adjacent the second charge-carrier collector may be interposed between the first doped element and
10 the third doped element. The oxide layer can act to decrease the resistance of the tunnel junction in the first charge-carrier collector compared to if the oxide layer was not present in the first charge-carrier collector and/or the oxide layer can act to increase the shunt resistance between the first charge-carrier collector and second charge-carrier collector. In this way, the current through the tunnel junction can be increased and/or a leakage current from the second doped element into the third doped element can
15 be reduced, thereby increasing the fill factor, current density, open-circuit voltage and efficiency of the solar cell.

The steps of the method of the fourth aspect may be executed in the order recited above. In another example, the steps of forming the third doped elements and forming the second doped elements may
20 both be conducted after forming the oxide layer.

In examples where the first doped elements are first doped silicon elements, the plasma treatment applied to the first doped silicon elements may be a carbon dioxide plasma treatment to form a SiO_x oxide layer on the first doped silicon elements, the second doped elements then being arranged on the
25 SiO_x layer.

Carbon dioxide plasma treatment may comprise exposing the surface to have hydrogen plasma treatment applied to it to a plasma comprising carbon dioxide molecules (i.e. CO_2) and plasma species derived therefrom (e.g. CO^+ , e^- , O^- , C^- , CO^- , C_2 , O_2), for example, the carbon dioxide plasma may
30 consist of carbon dioxide molecules and plasma species derived therefrom. The plasma to be used for carbon dioxide plasma treatment may not comprise silane, silanide, silylene, or other silicon-based gas species or plasma species derived therefrom. The carbon dioxide plasma treatment may be configured not to deposit additional silicon atoms onto the surface being treated.

In some examples, the plasma treatment may be applied to only the first doped elements, such that the oxide layer is formed on only the first doped elements.
35

The method according to the third and/or fourth aspect may further comprise the steps of: applying a mask over the back surface of the passivation layer prior to the step of applying the plasma treatment;
40 and removing the mask after the step of applying the plasma treatment. In this way, the plasma

treatment may be applied through the mask and the oxide layer on each first doped silicon element may comprise a first portion positioned for a tunnelling current through the first charge-carrier collector to flow through and a second portion positioned for a leakage current between the first charge-carrier collector and second charge-carrier collector to flow through, the second portion of the oxide layer being thicker than the first portion of the oxide layer. The increased thickness of the oxide layer at the second portion is due to concentration of plasma species at the edges of apertures through the mask. In this way, the oxide layer can act to simultaneously increase the shunt resistance in the solar cell between the first and second charge-carrier collectors and decrease the tunnelling resistance in the first charge-carrier collector.

Where the plasma treatment to form the oxide layer is a carbon dioxide plasma treatment, the carbon dioxide plasma treatment may be applied with one or more of the following conditions: a temperature of approximately 200°C, for example greater than or equal to 180°C and/or less than or equal to 200°C; a flowrate of carbon dioxide of approximately 250 standard cubic centimetres per minute, for example greater than or equal to 225 SCCM and/or less than or equal to 275 SCCM; a chamber pressure of approximately 80 Pascals, for example greater than or equal to 70 Pascals and/or less than or equal to 90 Pascals; a plasma power of approximately 300 watts, for example greater than or equal to 270 W and/or less than or equal to 330 W; a plasma frequency of approximately 27.12 MHz, for example greater than or equal to 24.0 MHz and/or less than or equal to 30.0 MHz; and a duration of approximately 10 seconds, for example greater than or equal to 8 seconds and/or less than or equal to 12 seconds.

The step of applying the mask may be conducted prior to the step of arranging the first doped elements. That is, it may be the same mask that is applied for the steps of arranging the first doped elements and applying the plasma treatment. In this way, the plasma treatment may be applied only to the first doped elements and thus the oxide layer may be formed on only the first doped elements.

In some examples, the steps of arranging the first doped elements and applying the plasma treatment to the first doped silicon elements may be conducted in the same deposition chamber as each other. By conducting steps of the methods in the same deposition chamber as each other, the number of instances of needing to move the partially-fabricated solar cell can be reduced, thereby simplifying the manufacturing process and reducing the manufacturing time compared to if movement between chambers is required, and reducing the likelihood of damaging the partially-fabricated solar cell when moving it between chambers, thereby reducing the rejection rate of solar cells from the manufacturing process and reducing material wastage.

In some examples, the methods may comprise a step of applying a mask to the back surface of the passivation layer prior to the step of arranging the first doped elements, the mask being applied such that it is in contact with the back surface of the passivation layer throughout the step of arranging the first doped elements.

In some examples, the mask may be applied to the back surface of the passivation layer such that it is in direct contact with (i.e. abuts) the back surface of the passivation layer. 'Throughout' as used here may be understood that the methods are executed such that the mask is in contact with the back surface of the passivation layer prior to the step of arranging the first doped elements commencing and is only subsequently moved out of contact with the back surface of the passivation layer after the step of arranging the first doped elements is completed (i.e., the first doped elements have been completely deposited). In this way, the manufacturing methods can be simplified compared to the method described in WO2021018517A1 where a first layer of its first doped elements is deposited with the mask hovering over passivation layer and subsequently the mask is in direct contact with the passivation layer when depositing the second layer of its first doped elements, because there is no requirement to accurately and consistently hover the mask over the substrate during a deposition step.

The mask may be a hard mask. The methods of manufacturing the solar cell may be configured to use only a single mask.

The steps carried out in the same deposition as each other may be conducted without moving the silicon wafer.

In some examples, the steps of arranging a plurality of second doped elements and arranging a plurality of third doped elements may be conducted simultaneously. The second doped elements and third doped elements may not be arranged by separate deposition processes but rather a single deposition process where the second and third doped elements are grown simultaneously. In this way, the second doped elements and third doped elements may be a single, continuous layer.

In a fifth aspect there is provided a solar module comprising one or more solar cells according to the first and/or second aspect.

The solar module (e.g., a solar panel) may define an apparatus for generating electrical power from sunlight. The solar module may comprise said one or more solar cells arranged (e.g., housed, or supported) in a structural frame, or housing. The one or more solar cells may be configured to absorb sunlight and generate electrical current.

The one or more solar cells may be configured with an electrical connector which enables electrical current to be extracted from the solar cells (e.g., to an electrical circuit of the solar module). The one or more solar cells and the electrical connector, when connected together, may define a solar cell assembly.

Two or more solar cells may be electrically connected in series (e.g., by one or more electrical connectors) to form a solar cell string. The solar module may comprise two or more solar cell strings, which may be electrically connected together in series and/or in parallel.

- 5 The solar module may comprise electrical circuitry which may be configured to extract electrical current from the solar panel to an external circuit (e.g., a second solar module).

According to a particular type of solar module, the solar cells may be arranged within a common transverse plane of the solar module. Accordingly, the widthwise and lengthwise dimensions of the plurality of solar cells may lie in the same plane. The first and second solar cells may be spaced apart by a gap in an in-plane direction (e.g., a lengthways and/or widthways direction) of the solar module. In this situation, the electrical connector (e.g., conductive elements, or wires) extend from the first solar cell to the second solar cell across a transition region (e.g., a gap) which is formed between the separated solar cells.

15

The one or more solar cells may comprise a substantially planar structure. For example, the solar cells may each comprise a length and/or a width which is substantially greater than its depth.

- 20 The one or more solar cells may each comprise a first (i.e., front) surface, upon which light from a radiative source (e.g., the sun) is incident during normal use, and a second (i.e., back) surface that is opposite the front surface. That is, the front surface may be configured in use to face the sun, whereas the back surface may be configured in use to face away from the sun.

- 25 The crystalline silicon-based wafer (i.e. the photovoltaic element) may define a substrate on which other layers of the solar cell are arranged (e.g., deposited). The photovoltaic element may comprise crystalline silicon (e.g., monocrystalline, or polycrystalline silicon). According to an exemplary arrangement, the photovoltaic element defines a crystalline silicon wafer which has been cut from an ingot, as will be understood by the skilled person.

- 30 The front and/or the back surface(s) of the solar cell may be textured to form a textured surface corresponding to an uneven surface (e.g., a surface having uneven characteristics). In this instance, an amount of light incident on the solar cell increases because of the textured surface of the solar cell, and thus the efficiency of the solar cell is improved.

- 35 The one or more solar cells may each have a substantially rectangular front and/or back surface. The solar cell may comprise four straight sides arranged at right angles to each other. One or more of the corners between the sides may be square, or pointed. Alternatively, the corners may be chamfered (or rounded), so as to define a pseudo-rectangular shape.

In exemplary arrangements in which the one or more solar cells are formed from a semiconductor wafer (e.g., a crystalline silicon wafer), the dimensions of each solar cell may substantially correspond to that of the wafer (e.g., a whole wafer silicon cell). The one or more solar cells may each be formed from a wafer which is cut into a plurality of sections. For example, the substantially planar wafer may be cut
5 along an in-plane direction (e.g., a width or length direction of the wafer) to define a cut solar cell (e.g., a half-cut solar cell).

As the solar cell comprises an interdigitated back contact, the back solar cell surface may be provided with two electrically conductive electrodes (e.g., a positive electrode and a negative electrode), which
10 may be configured to extract charge carriers from the solar cell. The electrodes may be formed of silver, or another suitably conductive material.

As outlined above, the solar cell is configured with a generally layered structure which includes first and second charge-carrier collectors configured to extract charge carriers from the substrate arranged on
15 the back surface thereof to provide an interdigitated back contact. The first charge-carrier collector may be an electron collector and the second charge-carrier may be a hole collector. Alternatively, the first charge-carrier collector may be a hole collector and the second charge-carrier may be an electron collector.

20 The solar cell may further include one or more passivation layers, regions of which are configured to passivate the interface between the substrate and a respective charge collector. The passivation layer may be interposed between the substrate and the interdigitated back contact, e.g. the regions of the passivation layer may be interposed between the substrate and the respective charge collector.

25 The substrate may divide the solar cell into a front portion which is forward (i.e., in front of) of the substrate, and a back portion which is rearward of the substrate. The solar cell defines an interdigitated back contact (IBC) solar cell, and in particular may define an IBC heterojunction solar cell, such that the back contact of the solar cell is arranged on the back portion of the solar cell.

30 During operation of the solar cell, incident light (e.g., directly from the sun) may pass through the front portion, the substrate and then the back portion. Alternatively, light may also be incident on the solar cell from a rearward direction (e.g., due to reflection of sun light by a surface behind the cell) such that it passes first through the back portion, then the substrate and then the front portion. In this way, the solar cell may be configured as a bifacial solar cell.

35

One or more of the solar cell's constituent elements may be configured with a width, a length, and a depth. The width and length of each element may be measured in perpendicular directions to each other and that are aligned with the front and back surfaces of the substrate. The depth (i.e. thickness) may be measured in a direction that is perpendicular to the front and back substrate surfaces. One or

more, or each, of the elements may be configured such that its width and/or length may be substantially greater than its depth.

5 According to an exemplary arrangement, the substrate may be formed from a monocrystalline silicon wafer. One or more of the constituent elements of the solar cell (e.g., the charge collector) may comprise an amorphous semiconductor material (e.g., amorphous silicon, a-Si) or a nano-crystalline material (e.g. nano-crystalline silicon nc a-Si).

10 One or more of the constituent elements of the solar cell (e.g., the substrate and/or the charge collector) may be at least partially doped to provide a prescribed conductivity type. The passivation element/layer may be configured with no conductivity type such that it forms an intrinsic layer (e.g., non-doped) between the charge collectors and the substrate.

15 A constituent element (or layer) of the solar cell may be configured with a determined conductivity type (e.g., p-type or n-type). In some cases, the semiconductor material making up an element or layer may not be doped (e.g., such as with an intrinsic passivation element/layer).

20 The substrate may be configured with a first conductivity type (e.g., n-type) and another element (e.g., a charge collector) may be 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 along with the substrate. According to such an arrangement, the charge collector may define a minority charge carrier collector (e.g., a hole collector) of the solar cell.

25 During operation of the solar cell, a plurality of electron-hole pairs is produced by light incident on the substrate.

30 When the substrate is n-type and a minority charge carrier collector is p-type (e.g., a hole-collector), the separated holes and electrons move to the p-type hole collector and the n-type substrate, respectively. Accordingly, the holes operate as majority charge carriers in the p-type hole collector, and the electrons operate as majority charge carriers in the n-type substrate.

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

40 In exemplary arrangements the solar cell comprises a first charge-carrier collector comprising the first doped element and a second charge-carrier collector comprising the third doped element. The first charge-carrier collector may define a majority charge-carrier collector configured with the first conductivity type (e.g., n-type), which is the same as that of the substrate. The majority charge-carrier

collector may be configured to selectively screen, or extract, electrons carriers from the substrate. For example, in exemplary arrangements wherein both the substrate and the majority charge-carrier collector are n-type, the majority charge-carrier collector defines an electron collector. Accordingly, when the solar cell is in use, the electrons produced by light incident on the substrate may be collected in the electron collector, wherein they operate as majority charge carriers.

Such an arrangement contributes towards the formation of a heterojunction technology (HJT) type solar cell, which is so defined because it combines two different materials to create a charge separating p-n junction. Accordingly, the solar cell may define a heterojunction type (HJT) solar cell.

When a semiconductor material is n-type, it may be configured to contain impurities (i.e. dopants) of a group V element such as phosphorus (P), arsenic (As), and antimony (Sb).

When a semiconductor material is p-type, it may contain impurities (i.e. dopants) of a group III element such as boron (B), gallium (Ga), and indium (In).

The solar cell may further comprise an anti-reflection element, layer, or coating, arranged on an opposite side of the solar cell to the interdigitated back contact (e.g., such that the substrate is interposed between the anti-reflection layer and the interdigitated back contact). The anti-reflection layer may be on the front side of the cell. The anti-reflection layer advantageously reduces the reflectance of light incident on the solar cell and increases selectivity of a predetermined wavelength band, thereby increasing the efficiency of the solar cell.

The solar cell may further comprise a back-reflector layer to reflect photons that have passed through the substrate back towards the substrate. The back-reflector layer may be provided within the interdigitated back contact. By way of example, the back-reflector layer may be interposed between the interdigitated back contact and electrodes arranged on the IBC to collect charge carriers therefrom. The back-reflector layer may be deposited as a uniform layer over a back surface of the second and third doped elements; subsequently, portions of the back-reflector layer arranged on the second and third elements may be isolated from each other e.g. using screen printed resists and a wet chemical process. Alternatively, portions of the back-reflector layer may be deposited separately on the second and third elements, respectively, such that they are isolated from each other. The electrodes may have a smaller cross-sectional area in a plane parallel to the back surface of the substrate than respective isolated portions of the back-reflector layer they are arranged on.

The solar cell may comprise a transparent conductive oxide (TCO) layer. For example, the anti-reflection layer and/or the back-reflector layer may be formed of a transparent conductive oxide material, such as indium tin oxide (ITO). A surface of the substrate (e.g., the substrate's front and/or back surface(s)) may be textured.

One or more, or each, of the layers within the solar cell's layered structure may substantially conform with the substrate's textured surface, such that the anti-reflection layer defines a textured outer surface of the solar cell (e.g., the solar cell's front and/or back surface).

- 5 The solar cell may comprise an electrode (e.g., a finger 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 one or more of the charge-carrier collectors is interposed between the electrode and the substrate.
- 10 According to an exemplary method of manufacturing a solar cell, the method may comprise arranging the substrate in a processing vessel (e.g., a deposition chamber) and then depositing one or more, or each, of the layered structure's constituent layers onto the substrate.

- The method may comprise using a vapour deposition process in which one or more gases are introduced into the deposition chamber so as to form chemical species which are deposited onto an exposed surface (e.g., an exposed surface of the substrate).
- 15

- The deposition process may be a chemical vapour deposition process (CVD), e.g., a plasma enhanced chemical vapour deposition process (PECVD), as would be understood by the skilled person.
- 20

- Two or more of the solar cell's constituent elements (e.g., a charge-carrier collector and/or passivation element/layer), may be deposited using the same deposition method as a part of a single continuous process. It will be understood that although they are deposited using a similar deposition method, One or more, or each, of the constituent elements (e.g., a charge collector and/or passivation element) may be deposited in different deposition steps, and/or in different deposition chambers.
- 25

- In exemplary arrangements which comprise a plurality of solar cells, the solar cells may be connected so that electrical current is conducted, via an electrical connector, from one solar cell to another. The electrical connector may comprise one or more electrically conductive elements (e.g., wires, or cables) which form an electrical connection between electrically conductive surfaces (e.g., electrodes, or contacts) of two or more of the solar cells.
- 30

- The electrical connector may be configured to connect a back surface of a second solar cell. The electrical connector may comprise a first section for forming an ohmic connection to the first charge-carrier collector of the first solar cell, a second section for forming an ohmic connection to second charge-carrier collector of the second solar cell (i.e., a back connector), and a third section configured to connect (e.g., directly, or indirectly) the first section to the second section. The third section may, in this way, define an interconnector configured to electrically couple together the respective first and second sections.
- 35

40

In exemplary arrangements in which the electrical connector comprises a plurality of conductive elements, the first section of each of the conductive elements may together define the negative electrode connector. Similarly, the second sections may define the positive electrode connector.

- 5 One or more, or each, of the conductive elements may comprise an elongate form, such as a wire or wire portion. The one or more, or each, conductive element may comprise a single integrally formed element (e.g., a wire). Configuring the conductive elements in this way removes the need to provide separate connections (such as copper ribbons) between overlapping solar cells, which thereby reduces the number and complexity of manufacturing steps required to fabricate the solar cell assembly.

10

Each of the conductive elements may comprise a width, an axial length, and a depth. Each of the conductive elements may be configured such that its axial length is substantially greater than its width and/or depth. The width and axial length of the conductive elements may be measured in perpendicular directions aligned with a plane of the surface of the solar cell upon which the conductive elements are arranged (e.g., the front or back surface of the solar cell). The depth (e.g., thickness) may be measured in a direction which is perpendicular to the same plane of the solar cell.

15

The conductive element(s) may be formed of an electrically conductive material, such as a metallic or metallic alloy material, which may comprise at least one of Ag, Al, Au, and Cu.

20

According to an exemplary arrangement, each of the plurality of conductive elements may comprise a coating (not shown) which is configured, when in use, to solder the conductive elements to the respective surfaces of the solar cells upon which they are overlaid.

- 25 The coating (i.e., the solderable coating) may comprise an electrically conductive material having a melting point which is lower than that of the conductive element. The coating may comprise a metal alloy formed of two or more components. The coating alloy may be at least one of a lead based, tin based and bismuth-based alloy. The coating may comprise a 2-phase, 3-phase, or more complex metal alloy. The coating may be formed of a metal alloy comprising one or more of Ag, Bi, Cd, Ga, In, Pb, Sn, 30 Ti, etc. The coating may also comprise an electrically conductive material which is formed of metallic, or alloy particles embedded within an organic matrix.

The electrical connector may define an electrode assembly comprising one or more electrically conductive elements (e.g., a busbar) which are mounted to a surface of the solar cell, and a separate 35 wire (e.g., a cable, or ribbon) which electrically couples the conductive element to a circuit that is external to the solar cell. For example, the electrode assembly may comprise a copper cable which connects a plurality of busbars arranged on the back surface of the first solar cell in connection with the first charge-carrier collectors to a plurality of busbars arranged on the back surface of the second solar cell in connection with the second charge-carrier collectors.

40

Each of the solar cells' conductive surface(s) may comprise a plurality of finger electrodes which extend substantially across the respective solar cell surfaces. The finger electrodes may be formed using a printed material, which enables them to be conveniently deposited onto the surface(s) of the solar cells.

5 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–
10 voltage (I-V) characteristic).

It will be understood that when an element such as a layer, film, region, or substrate is referred to as being "on" another element (e.g. "arranged on" another element), it can be directly "on" (e.g. "arranged directly on") the other element or intervening elements may also be present (e.g. "arranged indirectly
15 on"). In contrast, when an element is referred to as being "directly on" another element (e.g. "arranged directly on"), there are no intervening elements present.

The terms "front" and "forward" are used herein to refer to a direction towards a light source (e.g. the sun) in use and orthogonal to a front surface of the solar module, and the terms "rear", "back" and
20 "rearwardly" are intended to refer to a direction that is opposite to the front/forward direction.

The term "tunnel junction" is used herein to refer to a barrier, such as a thin insulating layer or electric potential between two electrically conducting materials. Electrons or holes pass through the barrier by quantum tunnelling. Across the tunnel junction the conduction band of one material is closely aligned
25 with the valence band of the other material.

The preceding summary is provided for purposes of summarising some examples to provide a basic understanding of aspects of the subject matter described herein. Accordingly, the above-described features should not be construed to narrow the scope or spirit of the subject matter described herein in
30 any way. Moreover, the above and/or proceeding examples may be combined in any suitable combination to provide further examples, except where such a combination is clearly impermissible or expressly avoided. Other features, aspects, and advantages of the subject matter described herein will become apparent from the following text and the accompanying drawings.

35

BRIEF DESCRIPTION OF THE DRAWINGS

Aspects, features, and advantages of the present disclosure will now be described by way of example only, with reference to the appended drawings in which like numerals denote like elements.

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Figs. 1A and **1B** are schematic plan views of a solar cell module including a plurality of solar cells, wherein Fig. 1A is a front view and Fig. 1B is a back view;

Fig. 2A is a schematic cross-sectional side view of a known tunnel-interdigitated back contact (IBC) solar cell showing, a substrate, a passivation layer, an IBC, and electrodes;

5 **Fig. 2B** is a schematic cross-sectional view of another known tunnel-IBC solar cell, showing a substrate, a passivation layer, an IBC, and electrodes;

Fig. 3A is a schematic cross-sectional view of a first tunnel-IBC solar cell according to the first aspect of the present disclosure, showing a substrate, a passivation layer, and an IBC;

10 **Fig. 3B** is a schematic cross-sectional view of a second tunnel-IBC solar cell according to the second aspect of the present disclosure, showing a substrate, a passivation layer, and an IBC;

Fig. 3C is a schematic cross-sectional view of a third tunnel-IBC solar cell according to the first and second aspects of the present disclosure, showing a substrate, a passivation layer, and an IBC;

Figs. 4A – 4F are schematic cross-sectional views of successive steps in forming the first tunnel-IBC solar cell in Fig. 3A;

15 **Fig. 5** is a flowchart for a first method of manufacturing a solar cell, the method being according to the third aspect of the present disclosure;

Figs. 6A – 6E are schematic cross-sectional views of successive steps in forming the second tunnel-IBC solar cell in Fig. 3B;

20 **Fig. 7** is a flowchart for a second method of manufacturing a solar cell, the method being according to the fourth aspect of the present disclosure;

Figs. 8A – 8G are schematic cross-sectional views of successive steps in forming the third tunnel-IBC solar cell in Fig. 3C;

Fig. 9 is a flowchart for a third method of manufacturing a solar cell, the method being according to the third and fourth aspects of the present disclosure; and

25 **Fig. 10** is an I-V plot for the first tunnel-IBC solar cell and third tunnel-IBC solar cell.

DETAILED DESCRIPTION

30 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.

35 Figs. 1A and 1B show a solar cell module 100 (e.g., solar panel) according to the present disclosure. The solar cell module 100 includes a plurality of solar cells (including a first solar cell 20 and a second solar cell 30) which are arranged within a housing 102 (e.g., a structural frame, or support) of the solar module 100, as will be described in more detail below. The solar cells are sandwiched between a front plate 104 and a back plate 108 of the solar module housing 102, as is shown in Fig. 2A.

40 The solar module 100 includes electrical circuitry (e.g., an electrical assembly) to enable electrical power to be extracted from the solar cells arranged inside the module housing 102. The electrical

circuitry includes a pair of electrical connectors 112 (as shown in Fig. 1b) which couple the module 100 to an external circuit (e.g., two adjacent solar modules). The external connector 112 is connected, at one end, to a junction box 110 which is arranged on the back side of the solar module 100 (e.g., mounted to the back plate 106). At least one further connector provides an electrical connection
5 between the junction box 110 and the solar cells which are arranged within the module 100 (e.g., an internal connector). The electrical circuitry may include one or more diodes (e.g., bypass diodes) which regulate the flow of charge between the solar cells and/or between the solar module and the external electrical circuit. The electrical circuitry components can be arranged within the junction box and/or within the module housing itself. It will be appreciated that the solar module may comprise a plurality of
10 connectors and/or junction boxes as appropriate.

The solar module 100 has a length which is the horizontal dimension of Figs. 1a and 1b, a width which is the vertical direction of Figs. 1a, 1b and 2a, and a height (or thickness) which is substantially into the page of Figs. 1A, and 1B, and the vertical direction of Fig 2A.

15 According to the exemplary arrangement shown in Fig. 1A, the solar module 100 includes ninety-six solar cells arranged in a rectangular array comprising six rows and sixteen columns (arranged horizontally and vertically, in Fig. 1A, respectively). It will be appreciated that the solar module 100 may be configured with any number of solar cells (e.g., arranged in different array shapes, and comprising
20 different numbers of columns and rows), without departing from the scope of the present disclosure. At least some of the solar cells are electrically coupled together (e.g., in series) to form a solar cell string. The solar module 100 includes a plurality of solar cell strings. At least some of the strings are electrically coupled together in series. Two or more of the strings may be coupled together in parallel. Different strings may be connected together using one or more cross-connectors which are mounted within the
25 solar module housing 102.

The front plate 104 of the module housing 102 comprises a transparent (e.g., glass) sheet which is configured to allow light to pass through into a central chamber in which the solar cells 20, 30 are mounted. The back plate 108 is arranged to enclose the solar cells 20, 30 within the central chamber.
30 The back plate 108 comprises a reflective sheet which reflects any light incident upon its front surface (i.e., front facing surface) back towards the solar cells. The central chamber is filled with an encapsulating material that prevents ingress of fluid entrants which could degrade the solar module's performance.

35 Fig. 2A is a schematic cross-sectional side view of a known tunnel-interdigitated back contact (IBC) solar cell. The solar cell comprises an n-doped substrate 60, the lower face of which is configured to receive incoming light, and on the back surface of which is provided an undoped amorphous silicon passivation layer 70 to reduce the recombination rate of charge-carriers at the back surface of the substrate 60. The back surface of the substrate 60 defines an X-Y plane, with a vertical Z axis that is
40 orthogonal to the X-Y plane and corresponds to a thickness direction of the solar cell. A first charge-

carrier collector is provided in the solar cell of Fig. 2A by first, n-doped, silicon elements 66 arranged in a fingered pattern on the back surface of the passivation layer 70 and second, p-doped, silicon elements 68 arranged on the first silicon elements 66. The first silicon elements 66 are amorphous silicon adjacent the passivation layer 70, and transition to being at least partially micro- or nano-crystalline towards their back surface away from the passivation layer 70 and adjacent the second silicon elements 68. The second silicon elements 68 are micro- or nano-crystalline silicon as a result of being grown on the nanocrystalline back surface of the first silicon elements 66. The first and second silicon elements 66, 68 thus provide a first charge-carrier collector on the back surface of the passivation layer 70 that is a tunnel junction electron collector. A negative electrode 56 is provided on the back surface of the first charge-carrier collector. A second charge-carrier collector is provided in the solar cell of Fig. 2A by a third, p-doped, silicon element 67 interposed between the two fingers of the first silicon elements 66. The third silicon element 67 comprises an amorphous portion 67a immediately adjacent the passivation layer 70 and a microcrystalline portion 67b on the back surface of the amorphous portion 67a and thus further away from the passivation layer 70. The third silicon element 67 thus provides a second charge-carrier collector on the back surface of the passivation layer 70 that is a hole collector. A positive electrode 58 is provided on the back surface of the first charge-carrier collector. The lower crystallinity of the amorphous portion 67a (and the third silicon element 67 more generally) compared to the nanocrystalline first silicon element 66 and nanocrystalline second silicon element 68 increases the shunt resistance between the hole and electron collectors adjacent the passivation layer 70 and thus reduces leakage current in the solar cell. However, due to the amorphous portion 67a, the contact resistance of the third silicon element 67 (and thus the hole collector) is high. Nevertheless, reducing the thickness of the amorphous portion 67a is unattractive because doing so would reduce the shunt resistance of the cell.

Fig. 2B is a schematic cross-sectional side view of another known tunnel-interdigitated back contact (IBC) solar cell. The solar cell of Fig. 2B comprises an n-doped substrate 60, the lower face of which is configured to receive incoming light, and on the back surface of which is provided an undoped amorphous silicon passivation layer 70 to reduce the recombination rate of charge-carriers at the back surface of the substrate 60. The back surface of the substrate 60 defines an X-Y plane, with a vertical Z axis that is orthogonal to the X-Y plane and corresponds to a thickness direction of the solar cell. A first charge-carrier collector is provided in the solar cell of Fig. 2A by first, n-doped silicon elements 66 arranged in a fingered pattern on the back surface of the passivation layer 70 and second, p-doped silicon element 68 arranged on the first silicon elements 66. The first silicon elements comprise a first portion 66a arranged directly on the back surface the passivation layer 70 and a second portion 66b arranged on the first portion 66a and spaced from the passivation layer 70. The first portion 66a is amorphous silicon and the second portion 66b has a nano crystalline structure, and the first portion 66a has a dimension in a plane parallel to the X-Y plane that is greater than a dimension of the second portion 66b in a plane parallel to the X-Y plane (e.g. in the cross-section in Fig. 2B, the first portion 66a has a greater maximum width in the Y-axis than the second portion 66b). The second silicon element 68 arranged on the second portion 66b of the first silicon element 66 is nano-crystalline and together

with the first silicon element 66 provides a tunnel junction in the first charge-carrier collector. The first charge-carrier collector is an electron collector as a result of the n-type doping of the first silicon element 66. A negative electrode 56 is provided on the back surface of the first charge-carrier collector. A second charge-carrier collector is provided in the solar cell of Fig. 2B by a third, p-doped, silicon element 67 interposed between the two fingers of the first silicon elements 66. The second charge-carrier collector is the hole collector as a result of the p-type doping of the third silicon element 67. A positive electrode 58 is provided on the back surface of the first charge-carrier collector. The third silicon element 67 is formed as a single, continuous layer with the second silicon elements 68 such that the third silicon element 67 is also nanocrystalline. By the amorphous first portions 66a of the first silicon elements 66 having a greater width than the nanocrystalline second portions 66b of the first silicon elements 66, separation between the nanocrystalline second portions 66b of the first silicon elements in the electron collector and the nanocrystalline third silicon element 67 in the hole collector is provided. This separation acts to increase the shunt resistance between these parts of the solar cell. Leakage current between the first portions 66a of the first silicon elements 66 and the third silicon element 67 is low because the first portions 66a are amorphous and the third silicon element 67 is nanocrystalline and the separation between the nano-crystalline second portions 66b of the first silicon elements 66 and the nano-crystalline third silicon element 67 means that the leakage current therebetween is low compared to if they abutted each other. However, the presence of the amorphous first portion 66a of the first silicon elements 66 increases the contact resistance of the first silicon elements 66 (and thus the electron collector). Moreover, manufacture of the solar cell in Fig. 2B either requires the creation of multiple patterns (e.g. by the use of multiple masks) or requires a mask to be hovered above the substrate without contacting a deposition surface when depositing the first portions 66a of the first silicon element 66 as described in WO2021018517A1.

Thus, the solar cells / modules and methods of manufacturing said solar cells / modules according to the present disclosure has been developed in light of a desire to reduce hole and electron contact resistance, reduce leakage current between adjacent contacts, and further simplify manufacturing techniques compared to the known solar cells in Figs. 2A and 2B.

Fig. 3A is a schematic cross-sectional view of a first tunnel-IBC solar cell according to the first aspect of the present disclosure. The structure illustrated in Fig. 3A is discussed below in conjunction with Figs. 4A – 4F that are schematic cross-sectional views of successive steps in forming the first tunnel-IBC solar cell in Fig. 3A and Fig. 5 that is a flowchart for a method of manufacturing the first tunnel-IBC solar cell.

The first tunnel-IBC solar cell in Fig. 3A comprises a substrate 60 that is a crystalline silicon-based wafer. The substrate 60 comprises n-type dopant atoms (e.g. one or more group V atoms such as phosphorus (P), arsenic (As), and antimony (Sb)) such that the conductivity type of the substrate is negative. The substrate 60 is substantially planar, having a width and length in the X- and Y- axes, respectively, that is substantially greater than its thickness in the Z-axis. The orientation of the first solar

cell in Fig. 3A is such that a front surface of the substrate 60 through which photons enter the substrate is facing the vertically downwards direction, whilst the back surface of the substrate 60 faces vertically upwards. Step S110 in Fig. 5 comprises providing a crystalline silicon-based wafer comprising a back surface as the substrate 60 to arrange the remainder of the solar cell on. Fig. 4A illustrates such a substrate 60 without any other elements of the solar cell provided thereon.

Arranged directly on the back surface of the substrate 60 is a passivation layer 70. The purpose of the passivation layer 70 is to passivate the interfaces between the substrate 60 and respective charge collectors 80, 90 in the interdigitated back contact (IBC). As is described in greater detail below, there are positive (i.e. hole) and negative (i.e. electron) charge-carrier collectors 80, 90 within the IBC. Accordingly, the passivation layer 70 can be considered to comprise first regions that passivate the interfaces between the substrate 60 and the negative charge-carrier collectors 80 and second regions that passivate the interfaces between the substrate 60 and the positive charge-carrier collectors 90. The passivation layer 70 is typically formed of an intrinsic (e.g. non-doped) hydrogenated amorphous silicon layer (a-Si:H(i)). At step S120 in Fig. 5, the a-Si:H(i) passivation layer 70 is arranged on the substrate 60 by way of a deposition process (e.g. plasma-enhanced chemical vapour deposition (PECVD)) as illustrated in Fig. 4B. The passivation layer 70 comprises a back surface that is on the opposite side of the passivation layer 70 to the substrate 60.

As mentioned above, the solar cell further comprises an IBC, the IBC comprising a plurality of negative charge-carrier collectors (i.e. electron collectors) 80 interdigitated with a plurality of positive charge-carrier collectors (i.e. hole collectors) 90. In the cross-sectional view of Fig. 3A the alternating arrangement of electron collectors 80 and hole collectors 90 in the lengthwise direction of the solar cell (Y-Axis direction) can be seen. A typical arrangement is for the charge-carrier collectors 80, 90 to be elongate, such that they would have a length extending in the X-axis (i.e. the width wise direction of the solar cell) that is substantially greater than the width of the charge carriers (i.e. the charge-carrier collectors' 80,90 dimensions in the Y-Axis) illustrated in Fig. 3A, e.g. the length of the charge-carrier collectors 80, 90 may be such that each charge-carrier collector 80, 90 extends across the width of the solar cell.

The back surface of the passivation layer in Fig. 3A is shown to comprise a plurality of first regions 70b underlying the electron collector 80 and a plurality of second regions 70c underlying the hole collector 90. The first regions 70b and second regions 70c are differentiated from each other by having a different concentrations of hydrogen atoms within the a-Si:H(i) structure, with the first regions 70b having a lower concentration of hydrogen atoms than the second regions 70c. This difference in hydrogen concentration in the a-Si:H(i) structure between the different regions is realised after the step of depositing the passivation layer 70 by applying hydrogen plasma treatments to the partially-fabricated solar cell during the manufacturing process. In particular, in the method of manufacturing the first tunnel-IBC solar cell in Fig. 3A, the method comprises step S130 where a first hydrogen plasma treatment is applied to the whole of the passivation layer 70 from the back surface thereof. This is illustrated in Fig.

4C, where the entire back surface of the passivation layer 70 is exposed to a hydrogen plasma treatment to increase the concentration of hydrogen atoms in the a-Si:H(i) structure in the passivation layer (in particular, at the back surface thereof) to a concentration that corresponds to the concentration of hydrogen atoms in the first regions 70b of the solar cell once fabrication is completed. Steps S120 and S130 may be conducted in the same deposition chamber as each other. Following several intervening steps of the manufacturing method (which are discussed below), a second hydrogen plasma treatment is applied to the partially-fabricated solar cell at step S170, as illustrated by Fig. 4E. However, at the point step S170 is executed, only the second regions 70c of the back surface of the passivation layer 70 are still exposed, the first regions 70b having been covered by other elements of the solar cell (discussed further below), and consequently, the second hydrogen plasma treatment increases the concentration of hydrogen atoms in the a-Si:H(i) structure at the second regions 70c of the passivation layer 70, but does not increase the concentration of hydrogen atoms in the a-Si:H(i) structure at the first regions 70b of the passivation layer. The hydrogen plasma treatments improve passivation at the c-Si / a-Si:H(i) interface by replacing weak Si – H₂ bonds with Si – H bonds and can also etch the a-Si:H(i) layer and provide seed layers for nano- / micro-crystalline growth of a subsequent layer thereon. The parameters of the hydrogen plasma treatments can be tailored to providing the desired balance of these effects. The first and second hydrogen plasma treatments are discussed further below.

Returning to the intervening steps between the first and second hydrogen plasma treatments S130, S170, at step S140 the fabrication of the IBC commences with the electron collector 80. As illustrated in Fig. 3A, the electron collector 80 comprises a plurality of first doped silicon elements 66 arranged on the back surface of the passivation layer 70 overlying the first regions 70b thereof and a plurality of second doped silicon elements 68 arranged directly on the first doped silicon elements 66. The first doped silicon elements 66 comprise n-type dopant atoms such as to have n-type conductivity and are formed of nano-crystalline silicon (nc-Si:H(n)), whilst the second doped silicon elements 68 comprise p-type dopant atoms such as to have p-type conductivity and are formed of nano-crystalline silicon (nc-Si:H(p)). Consequently, the second doped silicon elements 68 being arranged directly on the first doped silicon elements 66 provides the electron collector 80 with a tunnel-junction.

To provide the interdigitated nature of the electron and hole collectors 80, 90, the plurality of first doped silicon elements 66 are deposited onto the passivation layer 70 in a spaced apart from each other in the Y-axis direction. To provide said spacing when depositing the first doped silicon elements 66 using a chemical vapor deposition process (e.g. PECVD), a mask 1 is first applied to back surface of the passivation layer 70 at step S140 and subsequently at step S150 the first doped silicon elements 66 are deposited onto the back surface passivation layer 70 through the mask 1 (e.g. using PECVD). This is illustrated by Fig. 4D in which the regions of the passivation layer 70 on which the first doped semiconductor elements 66 are formed is where the passivation layer 70 is exposed through apertures in the mask 1. Fig. 4D illustrates how the width (and hence cross-sectional area) of each first doped silicon element 66 in an X-Y plane (i.e. parallel to the back surface of the passivation layer 70) decreases with increasing distance from the back surface of the passivation layer 70 as a result of

interactions between the mask 1 and the plasma that can lead to etching of the first doped silicon element 66, and also shadow effects caused by the mask 1. The mask 1 is applied to the back surface of the passivation layer 70 such that it is in direct contact with (i.e. abuts) the back surface of the passivation layer 70 throughout step S150.

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After step S150 is conducted, the mask 1 is removed from the back surface of the passivation layer 70 (step S160) to expose the second regions 70c of the passivation layer 70 that do not have the first doped silicon elements 66 arranged on them.

10 As illustrated in Fig. 3A the hole collector 90 in the first tunnel-IBC solar cell according to the present disclosure comprises a plurality of third doped silicon elements 67. The third doped silicon elements 67 comprise p-type dopant atoms such as to have p-type conductivity and are formed of nano-crystalline silicon (nc-Si:H(p))

15 To arrange a hole collector 90 on the passivation layer that has a low contact resistance, growth of third doped silicon elements 67 on the first regions of the passivation layer 70 that have a high crystalline fraction even immediately adjacent the passivation layer 70 is desired. However, realising nano-crystalline growth with a high crystalline fraction directly on an intrinsic amorphous silicon layer is challenging. Thus, prior to depositing the third doped silicon elements 67, the partially-fabricated solar
20 cell undergoes the second hydrogen plasma treatment at Step S170 in Fig. 5, as discussed above. The second hydrogen plasma treatment is applied after steps S150 and S160 and consequently the second hydrogen plasma treatment is applied to both the second regions 70c of the passivation layer 70 and back surfaces of the first doped silicon elements 66. The second hydrogen plasma treatment thus results in the concentration of hydrogen atoms in the second regions 70c of the passivation layer 70
25 being greater than that of the first regions of the passivation layer 70b and greater than that at the back surface of the first doped silicon elements 66. The effects of the second hydrogen plasma treatment in Fig. 4E is illustrated by the different hatching provided for the second regions 70c of the passivation layer 70 compared to the first regions 70b of the passivation layer 70 and by the black outline on the back surface of the first doped silicon elements 66.

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At step S180, a nano-crystalline p-doped silicon layer is deposited onto both the second regions 70c of the passivation layer 70 and the first doped silicon elements such as to simultaneously arrange the second doped silicon elements 68 of the electron collector 80 on the first doped silicon elements 66 and arrange the third doped silicon elements 67 on the second regions 70c of the passivation layer 70.

35 That is, the second doped silicon elements 68 and third doped silicon elements 67 may be provided as part of a single, continuous layer of nc-Si:H(p) material within the IBC.

However, the surface that the third doped silicon elements 67 are arranged on (i.e. the second regions 70c of the passivation layer) has been exposed to two hydrogen plasma treatments (the first and second
40 hydrogen plasma treatments), whilst the surface that the second doped silicon elements 68 are

arranged on (i.e. the back surface of the first doped silicon elements 66) has only been exposed to a single hydrogen plasma treatment (only the second hydrogen plasma treatment). Consequently, the crystalline fraction of the nc-Si:H(p) material forming the third doped silicon elements 67 is greater than the crystalline fraction of the nc-Si:H(p) material forming the second doped silicon elements 68. The difference in crystallinity between the second doped silicon elements 68 and third doped silicon elements 67 is illustrated by the different hatching in Fig. 3A and Fig. 4F. Steps S170 and S180 may be conducted in the same deposition chamber as each other.

The difference in the crystallinity between the second and third doped silicon elements 68, 67 increases the shunt resistance between the electron collector 80 and the hole collector 90. By increasing said shunt resistance, a leakage current from the electron collector 80 to the hole collector 90 can be reduced and in turn the current across the tunnel junction provided between the first doped silicon elements 66 and the second doped silicon elements 68 can be increased, thereby increasing the fill factor, current density, open circuit voltage and efficiency of the solar cell. Typically, the difference in the crystalline percentage of the third doped silicon elements 67 and the crystalline percentage of the second doped silicon elements is typically between 15% and 25%, however, this difference can be controlled by altering the parameters of the hydrogen plasma treatments applied to the partially-fabricated solar cell.

Table 1 below sets out typical parameters for the first hydrogen plasma treatment (HPT-1) and second hydrogen plasma treatment (HPT-2).

TABLE 1

Treatment	Temperature / °C	H ₂ Gas Flowrate / sccm	Pressure / Pa	Power / W	Plasma Frequency / MHz	Treatment Time / s
HPT-1	200	1000	80	700	13.56	15
HPT-2	200	9000	467	1000	27.12	10

Considering the structure of the IBC illustrated in Figs. 3A and 4F, it can be appreciated that the shape of the first doped silicon elements 66 in the cross section shown, in particular the fact that the width of each first doped silicon element 66 in an X-Y plane decreases with increasing distance from the back surface of the passivation layer 70, means that the interface between the electron collector 80 and the hole collector 90 in the IBC is predominantly formed between the third doped silicon elements 68 and second doped silicon elements 67. Accordingly, it is important that there is a large shunt resistance between these silicon elements as discussed above. However, it can also be envisaged that if the first doped silicon elements 66 were to have a different geometry (e.g. if the width of each first doped silicon element 66 was substantially constant with increasing distance from the back surface of the passivation layer 70) and/or the thicknesses of the first doped silicon elements 66 and the nc-Si:H(p) layer providing the second and third doped silicon element 68, 67 was adjusted, then the interface between the electron collector 80 and hole collector 90 in the IBC would be predominantly between the first doped silicon elements 66 and third doped silicon elements 67. In such an arrangement, it would be important for the

shunt resistance between these elements to also be large. Fortunately, the first tunnel-IBC solar cell described above would also provide a high shunt resistance between the first doped silicon elements 66 and third doped silicon elements 67 if they were in contact because the third doped silicon elements 67 would also have a higher crystalline fraction than the first doped silicon elements 66. Again, this is because the sequence of arranging elements within the IBC and applying hydrogen plasma treatments as described above means that the surface that the third doped silicon elements 67 are arranged on (i.e. the second regions 70c of the passivation layer 70) has been exposed to two hydrogen plasma treatments (the first and second hydrogen plasma treatments), whilst the surface that the first doped silicon elements 66 are arranged on (i.e. the first regions 70b of the passivation layer 70) has only been exposed to a single hydrogen plasma treatment (only the first hydrogen plasma treatment). The difference in the crystalline percentage of the third doped silicon elements 67 and the crystalline percentage of the first doped silicon elements 66 is typically greater than 10%, e.g. 15%.

Fig. 3B is a schematic cross-sectional view of a second tunnel-IBC solar cell according to the second aspect of the present disclosure. The structure illustrated in Fig. 3B is discussed below in conjunction with Figs. 6A – 6E that are schematic cross-sectional views of successive steps in forming the second tunnel-IBC solar cell in Fig. 3B and Fig. 7 that is a flowchart for a method of manufacturing the second tunnel-IBC solar cell.

The second tunnel-IBC solar cell in Fig. 3B comprises a substrate 60 that is a crystalline silicon-based wafer. The substrate 60 comprises n-type dopant atoms (e.g. one or more group V atoms such as phosphorus (P), arsenic (As), and antimony (Sb)) such that the conductivity type of the substrate is negative. The substrate 60 is substantially planar, having a width and length in the X- and Y- axes, respectively, that is substantially greater than its thickness in the Z-axis. The orientation of the first solar cell in Fig. 3B is such that a front surface of the substrate 60 through which photos enter the substrate is facing the vertically downwards direction, whilst the back surface of the substrate 60 faces vertically upwards. Step S210 in Fig. 7 comprises providing a crystalline silicon-based wafer comprising a back surface as the substrate 60 to arrange the remainder of the solar cell on. Fig. 6A illustrates such a substrate 60 without any other elements of the solar cell provided thereon.

Arranged directly on the back surface of the substrate 60 is a passivation layer 70. The purpose of the passivation layer 70 is to passivate the interfaces between the substrate 60 and respective charge collectors 80, 90 in the interdigitated back contact (IBC). As is described in greater detail below, there are positive (i.e. hole) and negative (i.e. electron) charge-carrier collectors 80, 90 within the IBC. Accordingly, the passivation layer 70 can be considered to comprise first regions that passivate the interfaces between the substrate 60 and the negative charge-carrier collectors 80 and second regions that passivate the interfaces between the substrate 60 and the positive charge-carrier collectors 90. The passivation layer 70 is typically formed of an intrinsic (e.g. non-doped) hydrogenated amorphous silicon layer (a-Si:H(i)). At step S220 in Fig. 7, the a-Si:H(i) passivation layer 70 is arranged on the substrate 60 by way of a deposition process (e.g. plasma-enhanced chemical vapour deposition

(PECVD)) as illustrated in Fig. 6B. The passivation layer 70 comprises a back surface that is on the opposite side of the passivation layer 70 to the substrate 60.

As mentioned above, the solar cell further comprises an IBC, the IBC comprising a plurality of negative charge-carrier collectors (i.e. electron collectors) 80 interdigitated with a plurality of positive charge-carrier collectors (i.e. hole collectors) 90. In the cross-sectional view of Fig. 3B the alternating arrangement of electron collectors 80 and hole collectors 90 in the lengthwise direction of the solar cell (Y-Axis direction) can be seen. A typical arrangement is for the charge-carrier collectors 80, 90 to be elongate, such that they would have a length extending in the X-axis (i.e. the width wise direction of the solar cell) that is substantially greater than the width of the charge carriers (i.e. the charge-carrier collectors' 80,90 dimensions in the Y-Axis) illustrated in Fig. 3B, e.g. the length of the charge-carrier collectors 80, 90 may be such that each charge-carrier collector 80, 90 extends across the width of the solar cell.

At step S240 the fabrication of the IBC commences with the electron collector 80. As illustrated in Fig. 3B, the electron collector 80 comprises a plurality of first doped silicon elements 66 arranged on the back surface of the passivation layer 70, a silicon oxide (SiO_x) layer 66' arranged directly on the first doped silicon elements 66, and a plurality of second doped silicon elements 68 arranged directly on the SiO_x layer 66' such that the SiO_x layer 66' on each first doped silicon element 66 is interposed between that first doped silicon element 66 and an overlying second doped silicon element 68. The first doped silicon elements 66 comprise n-type dopant atoms such as to have n-type conductivity and are formed of nano-crystalline silicon (nc-Si:H(n)). As discussed further below, the SiO_x layer 66' is formed from the nc-Si:H(n) elements 66 by way of a carbon dioxide plasma treatment applied thereto. Consequently, the SiO_x layer 66' comprises the same n-type dopant atoms as in the first doped silicon elements 66 and thus has the same doping type. The second doped silicon elements 68 comprise p-type dopant atoms such as to have p-type conductivity and are formed of nano-crystalline silicon (nc-Si:H(p)). The second doped silicon elements 68 are arranged directly on the SiO_x layer that is in turn arranged directly on the first doped silicon elements 66, thereby providing the electron collector 80 with a tunnel-junction between the first doped silicon elements 66, SiO_x layer 66', and second doped silicon elements 68.

To provide the interdigitated nature of the electron and hole collectors 80, 90, the plurality of first doped silicon elements 66 are deposited onto the passivation layer 70 in a spaced apart from each other in the Y-axis direction. To provide said spacing when depositing the first doped silicon elements 66 using a chemical vapor deposition process (e.g. PECVD), a mask 1 is first applied to back surface of the passivation layer 70 at step S240 and subsequently at step S250 the first doped silicon elements 66 are deposited onto the back surface passivation layer 70 through the mask 1 (e.g. using PECVD). This is illustrated by Fig. 6C in which the regions of the passivation layer 70 on which the first doped semiconductor elements 66 are formed is where the passivation layer 70 is exposed through apertures in the mask 1. Fig. 6C illustrates how the width (and hence cross-sectional area) of each first doped silicon element in an X-Y plane (i.e. parallel to the back surface of the passivation layer 70) decreases

with increasing distance from the back surface of the passivation layer as a result of interactions between the mask 1 and the plasma that can lead to etching of the first doped silicon element 66, and also shadow effects caused by the mask 1. The mask 1 is applied to the back surface of the passivation layer 70 such that it is in direct contact with (i.e. abuts) the back surface of the passivation layer 70 throughout step S250.

After step S250 is concluded and before removing the mask 1 from the back surface of the passivation layer 70, step S255 of applying a carbon dioxide plasma treatment to the first doped silicon elements 66 through the mask 1 is conducted in order to form the SiO_x layer 66' on back surfaces of the first doped silicon elements 66. By conducting the carbon dioxide plasma treatment with the mask 1 in place, it is possible to form the SiO_x layer 66' on only the first doped silicon elements 66 and not on regions of the passivation layer 70 that the first doped silicon elements 66 are not deposited on. The carbon dioxide plasma treatment comprises exposing the back surfaces of the first doped silicon elements to a plasma consisting of carbon dioxide molecules (i.e. CO_2) and plasma species derived therefrom (e.g. CO^+ , e^- , O^+ , C^+ , CO^+ , C_2 , O_2) in order to oxidise silicon atoms at, and adjacent, the back surface of the first doped silicon elements 66 in order to form a layer 66' comprising one or more different silicon oxide species (e.g. SiO , SiO_2 , SiO_3^{2-} , SiO_4^{4-}). Table 2 below sets out typical parameters for the carbon dioxide plasma treatment (COT). Steps S250 and S255 may be conducted in the same deposition chamber as each other.

Table 2

Treatment	Temperature / °C	CO_2 Gas Flowrate / sccm	Pressure / Pa	Power / W	Plasma Frequency / MHz	Treatment Time / s
COT	200	250	80	300	27.12	10

As can be appreciated from Fig. 6D, one of the features of the SiO_x layer 66' that results from conducting the carbon dioxide plasma treatment through the mask 1 is that the thickness of the SiO_x layer 66' varies with position on the underlying first doped silicon element 66. Thickness as used here refers to the dimension of the SiO_x layer 66' at a position of the layer and in a direction perpendicular to the back surface of the underlying first doped silicon element 66 at that position. Fig. 6D illustrates how the thickness of the SiO_x layer 66' at a first portion that is at a central position on the first doped silicon element (i.e. at a position midway between the edges of an aperture in the mask 1 in Fig. 6D) is less than the thickness of the SiO_x 66' layer at a second portion that is at a side of the first doped silicon element 66 (i.e. adjacent the edges of an aperture in the mask 1 in Fig. 6D). This variation in thickness can also be expressed as the thickness of the SiO_x layer 66' decreasing with increasing distance from the back surface of the passivation layer. Returning to Figure 3B that shows the fully-fabricated IBC, it can be appreciated that the first portions of the SiO_x layer 66' correspond to positions for a tunnelling current through the electron collector 80 to flow through and the second portions of the SiO_x layer 66' correspond to positions for the leakage current between the first doped silicon elements 66 of the electron collector 80 and the hole collector 90 to flow through.

The inventors have identified that by the SiO_x layer 66' being thicker at positions on each first doped silicon element 66 adjacent the hole collector 80 than at a central position on each first doped silicon element 66, the SiO_x layer 66' can act to simultaneously increase the shunt resistance between the electron collector 80 and hole collector 90 (i.e. where the SiO_x layer 66' is thicker) and decrease the resistance of the tunnel junction in the electron collector 80 (i.e. where the SiO_x layer 66' is thinner). In this way, a leakage current from the first doped silicon elements 66 into the third doped silicon elements 67 can be reduced and the current through the tunnel junction can be increased, thereby increasing the fill factor, current density, open-circuit voltage and efficiency of the solar cell. Typically, the thickness of the first portions of the SiO_x layer 66' is greater than 1.5 – 2 nm (e.g. 1 nm) such as to allow tunnelling therethrough, whilst the thickness of the second portions of the SiO_x layer 66' is less than 1.5 – 2 nm (e.g. 2.5 nm) to act as a resistive layer within the electron collector.

Having formed the SiO_x layer 66', at step S260 the mask 1 is removed from the back surface of the passivation layer 70 to expose the regions of the passivation layer 70 that do not have the first doped silicon elements 66 arranged on them.

As illustrated in Fig. 3B the hole collector 90 in the second tunnel-IBC solar cell according to the present disclosure comprises a plurality of third doped silicon elements 67. The third doped silicon elements 67 comprise p-type dopant atoms such as to have p-type conductivity and are formed of nano-crystalline silicon (nc-Si:H(p))

At step S280, a nano-crystalline p-doped silicon layer is deposited onto both the now-exposed regions of the passivation layer 70 and the SiO_x layer 66' such as to simultaneously arrange the second doped silicon elements 68 of the electron collector 80 directly on the SiO_x layer 66' and arrange the third doped silicon elements 67 directly on the passivation layer 70 for the hole collector 90. That is, the second doped silicon elements 68 and third doped silicon elements 67 may be provided as part of a single, continuous layer of nc-Si:H(p) material within the IBC as illustrated in Fig. 6E.

Because of the presence of the SiO_x layer 66' as discussed above, the interface between the second and third doped silicon elements 68, 67 in the structure shown in Figs. 3B and 6E does not give rise to high leakage currents from the electron collector 80 to the hole collector 90 because the thick second portions of the SiO_x layer 66' provide the second tunnel-IBC solar cell with a high shunt resistance in the portion of the IBC proximate the passivation layer 70 and simultaneously, the resistance to electrons tunnelling across the tunnel junction in the electron collector 90 is reduced by the thin first portion of the SiO_x layer 66' between the first and second doped silicon elements 66, 68.

Figure 3C is a schematic cross-sectional view of a third tunnel-IBC solar cell according to the first and second aspects of the present disclosure. The structure illustrated in Fig. 3C is discussed below in conjunction with Figs. 8A – 8G that are schematic cross-sectional views of successive steps in forming

the third tunnel-IBC solar cell in Fig. 3C and Fig. 9 that is a flowchart for a method of manufacturing the third tunnel-IBC solar cell.

It can be appreciated from Figs. 3C, 8A – 8G and Fig. 9 that the third tunnel-IBC solar cell is a combination of the first tunnel-IBC solar cell discussed above in relation to Figs. 3A, 4A – 4F and 5 and the second tunnel-IBC solar cell discussed above in relation to Figs. 3B, 6A – 6E and 7. That is, the third tunnel-IBC solar cell comprises both third doped solar cell elements 67 in the hole collector 90 that are more crystalline than the first doped silicon elements and/or second doped silicon elements in the electron collector 80 and an SiO_x layer 66' interposed between the first and second doped silicon elements 66, 68.

Consequently, the third tunnel-IBC solar cell is able to increase the shunt resistance between the electron collector 80 and hole collector 90 by the presence of the thick (and hence resistive) second portion of the SiO_x layer 66' between the first and third doped silicon elements 66, 67 and by the difference in crystallinity at the interface between the electron collector 80 and hole collector 90, as well as the thinner first portion of the SiO_x layer 66' at a central position on the first doped silicon elements 66 acting to reduce tunnelling resistance in the electron collector 80.

Given its similarities to both the first tunnel-IBC solar cell and second tunnel-IBC solar cell, a detailed description of the structure of the third tunnel-IBC solar cell is omitted and instead reference can be made back to the descriptions of the structures of the first and second tunnel-IBC solar cells described above.

Considering the flowchart in Fig. 9 for a method of manufacturing the third tunnel-IBC solar cell, it can be appreciated that steps S310 – S350 and S360 – S380 correspond to steps S110 – S180 in Fig. 5, respectively. The method in Fig. 9 differs from that of Fig. 5 by including step S355 of applying a carbon dioxide plasma treatment to the first doped silicon elements 66 through the mask 1 to form the SiO_x layer 66' on back surfaces of the first doped silicon elements 66. Step S355 is included between steps S350 of depositing the first doped silicon elements 66 and step S360 of removing the mask 1 from the passivation layer 70. Step S355 may be conducted in the same manner as step S255 discussed above with reference to Fig. 7.

Equivalently, it can be appreciated that Steps S310, S320, S340 – S360, and S380 in Fig. 9 correspond to steps S210 – S280 in Fig. 7, respectively. The method in Fig. 9 differs from that of Fig. 7 by including two further steps: step S330 where a first hydrogen plasma treatment is applied to the whole of the passivation layer 70 from the back surface thereof; and step S370 where a second hydrogen plasma treatment is applied, the second hydrogen plasma treatment being applied to both the second regions 70 of the passivation layer 70 and the SiO_x layer 66' (c.f. Step S270 in Fig. 7, where the second hydrogen plasma treatment is applied to the back surfaces of the first doped silicon elements 66). Step S330 may be conducted in the same manner as step S130 discussed above with reference to Fig. 5.

Step S370 may be conducted in the same manner as step S170 discussed above with reference to Fig. 5, albeit with the SiO_x layer 66' rather than the first doped silicon elements 66 receiving the second hydrogen plasma treatment (hence the black outline being provided on the back surface of the SiO_x layer 66' rather than on the second doped silicon elements 66). It can be appreciated that like with the first tunnel-IBC solar cell, the second hydrogen plasma treatment means that the passivation layer 70 surface that the third doped silicon elements 67 are arranged on has been exposed to two hydrogen plasma treatments (the first and second hydrogen plasma treatments), whilst the SiO_x layer 66' surface that the second doped silicon elements 68 are arranged on has only been exposed to a single hydrogen plasma treatment (only the second hydrogen plasma treatment). Consequently, the crystalline fraction of the nc-Si:H(p) material forming the third doped silicon elements 67 is greater than the crystalline fraction of the nc-Si:H(p) material forming the second doped silicon elements 68.

It can be appreciated that the methods of manufacturing the first, second and third tunnel-IBC solar cells described herein involve the use of only a single mask 1 that is always in contact with the passivation layer 70 when material is being deposited through the mask 1.

Positive and negative electrodes 54, 56 as illustrated in Figs. 2A and 2B may be applied to the back surfaces of the hole and electron collectors 90, 80 of any of the first, second and third tunnel-IBC solar cells described herein.

Figure 10 is an I-V plot for the first and third tunnel-IBC solar cells described above. Table 3 below provides corresponding performance metrics of the two solar cells. Although it involves additional processing steps in its manufacture (and thus increased manufacturing time and cost), the performance of the third tunnel-IBC solar cell is better than that of the first tunnel-IBC solar cell in terms of open circuit voltage (V_{oc}), fill factor (FF), conversion efficiency (CE) and pseudo fill factor (pFF). However, the first tunnel-IBC solar cell has a higher short-circuit current density (J_{sc}).

Table 3

Metric	First tunnel-IBC solar cell	Third tunnel-IBC solar cell
J_{sc} / mA/cm ²	42.59	41.87
V_{oc} / mV	741	746.11
FF / %	74.45	77.18
CE / %	23.52	24.11
pFF / %	81.10	82.57

It is to be understood that the present disclosure is not limited by specific construction details or process steps set forth in the following description and accompanying drawings. Rather, it will be apparent to those skilled in the art having the benefit of the present disclosure that the systems, apparatuses and/or methods described herein could be embodied differently and/or be practiced or carried out in various alternative ways.

Unless otherwise defined herein, scientific and technical terms used in connection with the presently disclosed inventive concept(s) shall have the meanings that are commonly understood by those of ordinary skill in the art, and known techniques and procedures may be performed according to conventional methods well known in the art and as described in various general and more specific references that may be cited and discussed in the present specification.

All examples implementing the present disclosure can be made and executed without undue experimentation in light of the present disclosure. While particular examples have been described, it will be apparent to those of skill in the art that variations may be applied to the systems, apparatus, and/or methods and in the steps or in the sequence of steps of the methods described herein without departing from the concept, spirit, and scope of the inventive concept(s). All such similar substitutions and modifications apparent to those skilled in the art are deemed to be within the spirit, scope, and concept of the inventive concept(s) as defined by the appended claims.

The use of the term “a” or “an” in the claims and/or the specification may mean “one,” as well as “one or more,” “at least one,” and “one or more than one.” As such, the terms “a,” “an,” and “the,” as well as all singular terms, include plural referents unless the context clearly indicates otherwise. Likewise, plural terms shall include the singular unless otherwise required by context.

The use of the term “or” in the present disclosure (including the claims) is used to mean an inclusive “and/or” unless explicitly indicated to refer to alternatives only or unless the alternatives are mutually exclusive. For example, a condition “A or B” is satisfied by any of the following: A is true (or present), and B is false (or not present), A is false (or not present), and B is true (or present), and both A and B are true (or present).

As used in this specification and claim(s), the words “comprising,” “having,” “including,” or “containing” (and any forms thereof, such as “comprise” and “comprises,” “have” and “has,” “includes” and “include,” or “contains” and “contain,” respectively) are inclusive or open-ended and do not exclude additional, unrecited elements or method steps.

Unless otherwise explicitly stated as incompatible, or the physics or otherwise of the embodiments, examples, or claims prevent such a combination, the features of examples disclosed herein, and of the claims, may be integrated together in any suitable arrangement, especially ones where there is a beneficial effect in doing so. This is not limited to only any specified benefit, and instead may arise from an “ex post facto” benefit. This is to say that the combination of features is not limited by the described forms, particularly the form (e.g., numbering) of example(s), embodiment(s), or dependency of claim(s). Moreover, this also applies to the phrase “in one embodiment,” “according to an embodiment,” and the like, which are merely a stylistic form of wording and are not to be construed as limiting the following features to a separate embodiment to all other instances of the same or similar wording. This is to say,

a reference to 'an,' 'one,' or 'some' embodiment(s) may be a reference to any one or more, and/or all embodiments, or combination(s) thereof, disclosed. Also, similarly, the reference to "the" embodiment may not be limited to the immediately preceding embodiment. Further, all references to one or more embodiments or examples are to be construed as non-limiting to the claims.

5

CLAIMS

1. A solar cell comprising:
- a substrate having a back surface;
 - 5 a passivation layer arranged on the back surface of the substrate, the passivation layer comprising a back surface; and
 - an interdigitated back contact, the interdigitated back contact comprising a first charge-carrier collector arranged on the back surface of the passivation layer and interdigitated with a second charge-carrier collector arranged on the back surface of the passivation layer;
 - 10 wherein:
 - the first charge-carrier collector comprises:
 - a plurality of first doped elements arranged on the back surface of the passivation layer, the first doped elements having a first conductivity type;
 - an oxide layer arranged on the first doped elements; and
 - 15 a plurality of second doped elements arranged on the oxide layer, the second doped elements having a second conductivity type that is opposite the first conductivity type; and
 - the second charge-carrier collector comprises a plurality of third doped elements arranged on the back surface of the passivation layer, the third doped elements having the second conductivity type.
- 20 2. A solar cell comprising:
- a substrate having a back surface;
 - a passivation layer arranged on the back surface of the substrate, the passivation layer comprising a back surface; and
 - an interdigitated back contact, the interdigitated back contact comprising a first charge-carrier
 - 25 collector arranged on the back surface of the passivation layer and interdigitated with a second charge-carrier collector arranged on the back surface of the passivation layer;
 - wherein:
 - the first charge-carrier collector comprises:
 - a plurality of first doped elements arranged on the back surface of the passivation layer,
 - 30 the first doped elements having a first conductivity type; and
 - a plurality of second doped elements arranged on the first doped elements, the second doped elements having a second conductivity type that is opposite the first conductivity type;
 - the second charge-carrier collector comprises a plurality of third doped elements arranged on the back surface of the passivation layer, the third doped elements having the second conductivity type;
 - 35 and
 - the third doped elements are more crystalline than the first doped elements and/or the second doped elements.

3. The solar cell according to claim 2, wherein the difference in the crystalline percentage of the third doped elements and the crystalline percentage of the second doped elements is greater than or equal to 5%.
- 5 4. The solar cell according to claim 2 or 3, wherein the solar cell further comprises an oxide layer arranged on the first doped elements and interposed between the first doped elements and the second doped elements.
5. The solar cell according to claim 1 or 4, wherein:
- 10 the oxide layer on each first doped element comprises a first portion positioned for a tunnelling current through the first charge-carrier collector to flow through and a second portion positioned for a leakage current between the first charge-carrier collector and second charge-carrier collector to flow through; and
- the second portion of the oxide layer is thicker than the first portion of the oxide layer.
- 15 6. The solar cell according to claim 5, wherein:
- the oxide layer is an SiO_x layer;
- the thickness of the first portion of the SiO_x layer is less than 2.0 nm; and
- the thickness of the second portion of the SiO_x layer is greater than or equal to 2.0 nm.
- 20 7. The solar cell according to any preceding claim, wherein:
- the passivation layer comprises hydrogenated amorphous silicon;
- the passivation layer comprises a plurality of first regions having a first concentration of hydrogen atoms and a plurality of second regions having a second concentration of hydrogen atoms,
- 25 the second concentration being lower than the first concentration; and
- the first doped elements are arranged on respective first regions of the passivation layer and the third doped elements are arranged on respective second regions of the passivation layer.
8. The solar cell according to any preceding claim, wherein the cross-sectional area of each first doped element in a plane parallel to the back surface of the passivation layer decreases with increasing distance from the back surface of the passivation layer.
- 30 9. The solar cell according to any preceding claim, wherein the second doped elements and third doped elements are a single, continuous layer.
- 35 10. The solar cell according to any preceding claim, wherein one or more of the substrate, the passivation layer, the first doped elements, the second doped elements, or the third doped elements comprises silicon, and, optionally, the substrate is a crystalline silicon-based wafer.
- 40 11. A method of manufacturing a solar cell, the method comprising the steps of:

- providing a substrate having a back surface;
arranging a passivation layer on the back surface of the substrate, the passivation layer comprising a back surface;
arranging an interdigitated back contact on the passivation layer, the interdigitated back contact comprising a first charge-carrier collector arranged on the back surface of the passivation layer and interdigitated with a second charge-carrier collector arranged on the back surface of the passivation layer, the step of arranging the interdigitated back contact comprising:
- arranging a plurality of first doped elements of the first charge-carrier collector on first regions of the back surface of the passivation layer, the first doped elements having a first conductivity type;
- applying a plasma treatment to the first doped silicon elements to form an oxide layer on the first doped silicon elements;
- arranging a plurality of second doped elements of the first charge-carrier collector on the oxide layer, the second doped elements having a second conductivity type that is opposite the first conductivity type; and
- arranging a plurality of third doped elements of the second charge-carrier collector on second regions of the back surface of the passivation layer, the third doped elements having the second conductivity type.
12. A method of manufacturing a solar cell, the method comprising steps of:
- providing a substrate comprising a back surface;
arranging a passivation layer on the back surface of the substrate, the passivation layer comprising a back surface;
arranging an interdigitated back contact on the passivation layer, the interdigitated back contact comprising a first charge-carrier collector arranged on the back surface of the passivation layer and interdigitated with a second charge-carrier collector arranged on the back surface of the passivation layer, the step of arranging the interdigitated back contact comprising:
- arranging a plurality of first doped elements of the first charge-carrier collector on first regions of the back surface of the passivation layer, the first doped elements having a first conductivity type;
- arranging a plurality of second doped elements of the first charge-carrier collector on the first doped elements, the second doped elements having a second conductivity type that is opposite the first conductivity type; and
- arranging a plurality of third doped element of the second charge-carrier collector on second regions of the back surface of the passivation layer, the third doped elements having the second conductivity type; and
- applying one or more hydrogen plasma treatments, the one or more hydrogen plasma treatments being applied to the passivation layer and/or the first doped elements such that the crystalline fraction of the third doped elements is different to the crystalline fraction of the first doped elements and/or the second doped elements.

13. The method according to claim 12, wherein the step of applying one or more hydrogen plasma treatments to the solar cell comprises applying a first hydrogen plasma treatment, the first hydrogen plasma treatment being applied to the passivation layer.
- 5
14. The method according to claim 13, wherein the step of applying one or more hydrogen plasma treatments to the solar cell comprises applying a second hydrogen plasma treatment, the second hydrogen plasma treatment being applied to the second regions of the passivation layer.
- 10
15. The method according to claim 14, wherein the second hydrogen plasma treatment differs from the first hydrogen plasma treatment by one or more of:
- a flowrate of hydrogen gas being different, optionally higher, during the second hydrogen plasma treatment than during the first hydrogen plasma treatment;
 - a chamber pressure being different, optionally higher, during the second hydrogen plasma treatment than during the first hydrogen plasma treatment;
 - 15 a plasma power density being different, optionally higher, during the second hydrogen plasma treatment than during the first hydrogen plasma treatment;
 - a plasma frequency being different, optionally higher, during the second hydrogen plasma treatment than during the first hydrogen plasma treatment; and
 - 20 a duration of the second hydrogen plasma treatment being different, optionally lower, than a duration of the first hydrogen plasma treatment.
16. The method according to claim 14 or 15, wherein:
- the steps of arranging the passivation layer on the back surface of the substrate and applying the first hydrogen plasma treatment are conducted in the same deposition chamber as each other; and/or
 - the steps of applying the second hydrogen plasma treatment and arranging the second doped elements and/or arranging the third doped elements are conducted in the same deposition chamber as each other.
- 30
17. The method according to any of claims 12 to 16, wherein the method further comprises the steps of:
- applying a mask over the back surface of the passivation layer prior to the step of arranging the first doped elements; and
 - 35 removing the mask after the step of arranging the plurality of first doped elements.
18. The method according to any of claims 12 - 17, wherein the difference in the crystalline percentage of the third doped elements and the second doped elements is greater than or equal to 10%.

19. The method according to any of claims 12 to 18, wherein the method further comprises a step of applying a plasma treatment to the first doped elements to form an oxide layer on the first doped elements.

- 5 20. The method according to claim 11 or 19, wherein:
 the oxide layer is a SiO_x layer; and
 the step of applying the plasma treatment to the first doped elements to form an oxide layer comprises applying a carbon dioxide plasma treatment.

- 10 21. The method according to any of claims 11, 19, or 20, wherein the steps of arranging the first doped elements and applying the plasma treatment to the first doped elements are conducted in the same deposition chamber as each other.

- 15 22. The method according to any of claims 11 to 21, wherein the method comprises a step of applying a mask to the back surface of the passivation layer prior to the step of arranging the first doped elements, the mask being applied such that it is in contact with the back surface of the passivation layer throughout the step of arranging the first doped elements.

- 20 23. The method according to claim 22 as dependent on any of claims 12, 19, 20, or 21, wherein the mask is applied to the back surface of the passivation layer such that it is in contact with the passivation layer throughout the step of applying the plasma treatment to form the oxide layer, such that the plasma treatment is applied through the mask and the oxide layer on each first doped element comprises a first portion positioned for a tunnelling current through the first charge-carrier collector to flow through and a second portion positioned for a leakage current between the first charge-carrier collector and second charge-carrier collector to flow through, the second portion of the oxide layer is thicker than the first portion of the oxide layer.

24. The method according to any of claims 12, 19, 20 or 21 wherein the method further comprises the steps of:
30 applying a mask over the back surface of the passivation layer prior to the step of applying the plasma treatment to form the oxide layer; and
 removing the mask after the step of applying the plasma treatment;
such that the plasma treatment is applied through the mask and the oxide layer on each first doped element comprises a first portion positioned for a tunnelling current through the first charge-carrier collector to flow through and a second portion positioned for a leakage current between the first charge-carrier collector and second charge-carrier collector to flow through, the second portion of the oxide layer being thicker than the first portion of the oxide layer.

25. The method according to any of claims 10 to 24, wherein the steps of arranging a plurality of second doped elements and arranging a plurality of third doped elements are conducted simultaneously.