SPECIFICATION

Amorphous silicon solar cells

The present invention relates to amorphous silicon solar cells. More particularly, the invention suggest a series of two or more layers of amorphous silicon arranged in a stacked configuration.

Photovoltaic devices, i.e., solar cells, are capable of converting solar radiation into useable electrical energy. The energy conversion occurs as a result of what is well known in the solar cell field as the photovoltaic effect. Solar radiation impinging on a solar cell and absorbed by an active region generates electrons and holes. The electrons and holes are separated by a built-in electric field, for example a rectifying junction, in the solar cell. This separation of electrons and holes results in the generation of an electrical current as explained below. For example, a built-in electric field can be generated in a solar cell by an active semiconductor layer with regions of P-type, intrinsic and N-type hydrogenated amorphous silicon. The electrons generated in the intrinsic region, by absorption of solar radiation of the appropriate bandgap, produce electron-hole pairs. The separation of the electron-hole pairs with the electrons flowing toward the region of N-type conductivity, and the holes flowing toward the region of P-type conductivity, creates the photovoltage and photocurrent of the cell.

The photocurrent output of a solar cell is maximized by increasing the total number of photons of differing energy and wavelength which are absorbed by the semiconductor material. The solar spectrum roughly spans the region of wavelength from about 300 nanometers to about 2200 nanometers, which corresponds to from about 4.2 eV to about 0.59eV, respectively. The portion of the solar spectrum which is absorbed by the solar cell is determined by the size of the bandgap energy of the semiconductor material. In the past, solar cells were fabricated from single crystal materials such as gallium arsenide, which has a bandgap energy of about 1.45 eV, or crystalline silicon, C-Si, which has a bandgap energy of about 1.1 eV. Solar radiation having an energy less than the bandgap energy is not absorbed by the semiconductor material, and thus does not contribute to the generation of the photocurrent output of the cell.

Semiconductor materials such as GaAS and C-Si have been utilized together in solar cells to increase the overall conversion of solar energy into electrical energy. However, problems are encountered with different semiconductor materials are used in the same solar cell. One solution to the problem of fabricating a solar cell structure with different semiconductor materials was to use filters to reflect light of the appropriate wavelength onto a solar cell of the first material and transmit the non-absorbed light to a cell of the second semiconductor material. A second solution used semiconductor materials of differing bandgaps which could be epitaxially grown on one another, such as aluminum gallium arsenide, gallium arsenide, and gallium phosphide structures. Both these systems have been loosely called tandem junction solar cells. A third alternative was to stack individual solar cells of differing bandgap energies and connect the cells in series. These three alternatives are either cumbersome, expensive and/or bulky.

Thus, it would be highly desirable to have a solar cell structure which could function as a tandem junction solar cell with separate active regions arranged in a stacked configuration without the need for light filters, or epitaxially matching one active region to another, or serially connecting separate solar cells.

According to the invention, there is provided an amorphous silicon solar cell comprising an electrically conductive substrate;

an active body having a first major surface ohmically contacting said substrate and a second major surface opposite to said first major surface, wherein said active body comprises a plurality of layers of hydrogenated amorphous silicon having regions of differing conductivity type, each of said layers forming a photovoltaic generator, said layers being arranged in stacked configuration such that the photovoltages from each of said layers is added, and a transparent tunnel junction is between each adjacent pair of layers of hydrogenated amorphous silicon;

a high work function metal cermet contacting said second major surface; and

means for electrically contacting said high work function metal cermet.

An embodiment of the invention comprises an improved solar cell structure which has a plurality of layers of hydrogenated amorphous silicon layers separated by a tunnel junction and arranged in a tandem stacked configuration. The thickness of the layers of amorphous silicon is adjusted to maximize efficiency and equalize the current generated in each layer. Optionally, tandem stacked hydrogenated amorphous silicon solar cells can have the bandgap of the hydrogentated amorphous silicon layers varied over the range of from about 1.5 eV to about 1.8 eV by adjusting the hydrogen concentration in the hydrogenated amorphous silicon layers.

IN THE DRAWINGS:—

Figure 1 illustrates a tandem junction hydrogenated amorphous silicon solar cell arranged in a stacked configuration wherein hydrogenated amorphous silicon layers are separated by a tunnel junction

Figure 2 illustrates a tandem junction hy-

drogenated amorphous silicon solar cell incorporating a grid electrode and a thick film cermet.

The invention will be more clearly illustrated by referring to Fig. 1. A tandem junction hydrogenated amorphous silicon solar cell is depicted as solar cell 10. Solar radiation 100 impinging upon the solar cell 10 is a reference point for the incident surface of each layer or region of the solar cell. The solar cell 10 includes a transparent substrate 12 of glass or other suitable material which is transparent to solar radiation. A transparent conductive oxide, hereinafter TCO, 14 is deposited on substrate 12 and forms an ohmic contact with a cermet layer 16 of $PtSiO_2$ containing from about 10 to about 40 volume percent of platinum and having a thickness of from about 2 to about 10 nanometers. Alternatively, the cermet layer 16 can be a cermet layer as taught in U.K. application No. 2019647, incorporated herein by reference, of a dielectric material such as TiO_2.

An active body 20, which comprises a plurality of layers of hydrogenated amorphous silicon wherein each pair of layers of hydrogenated amorphous silicon is separated by a transparent tunnel junction, is fabricated upon the cermet layer 16. In Fig. 1, the active body 20 has two layers 22 and 26 of hydrogenated amorphous silicon separated by a tunnel junction layer 24. The active body 20 can have from 2 to 5 or more layers of hydrogenated amorphous silicon.

A first active layer of hydrogenated amorphous silicon 22, comprised of regions 22a, 22b and 22c of differing conductivity type, is deposited on layer 16. Region 22a is an hydrogenated amorphous silicon layer doped with P-type conductivity modifiers such as boron or other suitable P-type dopants. Said region is from about 10 to about 40 nanometers thick and preferably about 37.5 nanometers thick. Region 22b is intrinsic hydrogenated amorphous silicon having a thickness of from about 50 to about 500 nanometers. Intrinsic hydrogenated amorphous silicon has been found to be of slightly N-type conductivity as reported in U.S. Patent 4,064,521 to Carlson, incorporated herein by reference. A region 22c of $N+$-type hydrogenated amorphous silicon, having a thickness of from about 10 to about 40 nanometers, is contiguous to the intrinsic hydrogenated amorphous silicon region 22b.

The tunnel junction layer 24 is situated between active layers 22 and 26 and provides a single electrical path through the first active layer 22 and the second active layer 26 to the back substrate 28. Layer 24 is from about 2 to about 15 nanometers thick and is comprised of a $PtSiO_2$ cermet, or a thin metal layer and a $PtSiO_2$ cermet, or a thin metal layer. The metal layer can be a metal such as platinum, titanium, nickel and like metals which are transparent to solar radiation. The performance of a tandem junction solar cell 10 is degraded if tunnel layer 24 is an insulator in spite of the fact that said insulator could be thin enough to permit electrons to tunnel therethrough.

Theoretically, tunnel layer 24 could be omitted if region 22c of N^+-type hydrogenated amorphous silicon and region 26a of P^+-type hydrogenated amorphous silicon could incorporate N-type and P-type conductivity modifiers in sufficient quantities to generate a tunnel junction between active layers 22 and 26. Although solar cell 10 can be fabricated without layer 24, sufficiently high doping levels to create a tunnel junction state with comparable performance to a $PtSiO_2$ cermet and like materials or a thin metal layer, have not been achieved in hydrogenated amorphous silicon.

The second active layer 26 comprises regions 26a, 26b, and 26c of hydrogenated amorphous silicon of differing conductivity type. Region 26a is similar to region 22a and incorporates suitable P^+-type dopants. Region 26b is similar to region 22b and region 26c is similar to region 22c. Optionally, regions 26a, 26b, and 26c may be deposited at a higher temperature to produce a layer with a lower concentration of hydrogen and a lower bandgap energy than active layer 22. The thickness of the second active layer 26 should be adjusted so that the current produced by said layer is about equal to the current produced by the first active layer 22 since the total current of the cell will be limited to the lower current of either active layer 22 or 26.

The absorption efficiency of the hydrogenated amorphous silicon solar cell approaches a constant when the intrinsic region thickness is about 500 nanometers. In a tandem junction solar cell, any additional thickness of this region only serves to increase the absorption of solar radiation without an increase in cell performance and robs any subsequent layers of the solar radiation. Therefore, the thickness of each intrinsic region should be thinner as the number of stacked hydrogenated amorphous silicon layers increases.

A metal film 28, such as titanium, molybdenum or niobium and like materials, which are adherent to and form a good ohmic contact with tne N^+-type hydrogenated amorphous silicon region 22c, is deposited on region 22c. Wires 15 and 29 are attached to metal layers 14 and 28 respectively to withdraw the current generated during illumination of the solar cell 10.

Another embodiment of the present invention is illustrated in Fig. 2. Fig. 2 illustrates a solar cell 50 with the substrate 12 in an inverted order to solar cell 10 of Fig. 1. Corresponding layers and regions of solar cells 50 and 10 have the same numbers in Fig. 2. Since solar radiation 100 does not have to

pass through the substrate 12, the substrate can be a metal layer such as stainless steel, molybdenum, titanium, and like materials. In addition, layer 14 in solar cell 50 is not needed to make the substrate electrically conductive.

Building the solar cell 50 in an inverted order permits the incorporation of a thick film ballast resistor cermet film layer 52, a grid electrode 56, and a TCO antireflection coating 58 into the cell structure. Layer 52 helps to minimize the effect of electrical shorts as taught in our U.S. Patent No. 4162505 which is incorporated herein by reference.

The solar cells of Fig. 1 and Fig. 2 may be fabricated by several methods. Layer 14 is deposited on the substrate 12 by evaporation or other methods known in the art such as electrochemical deposition. The cermet layer is fabricated in accordance with the teachings in the previously mentioned U.K. Application No. 2019647. The layers 22 and 26 of hydrogenated amorphous silicon are deposited by a glow discharge of silane or other appropriate silicon and hydrogen-containing atmosphere, as taught in the previously mentioned Carlson patent and U.K. Application No. 39992/77, also incorporated herein by reference. Layers 22 and 26 can also be fabricated with an RF deposition system. Suitable parameters for RF discharge are an RF power equal to or less than about 0.5 watt per square centimeter (w/cm^2), on a target having an area of about 160 cm^2, a gas pressure of from about 20 millitorr to about 50 millitorr, a silane flow rate of about 30 sccm and a system temperature of from about 200° to about 350°C. The P-type region of layers 22 or 26 is fabricated with a P-type dopant concentration of a suitable P-type dopant such as boron in the form of B_2H_6 from about 10^{-4} to about 10^{-5} percent of the deposition atmosphere. The N^+-type region is fabricated with a concentration of the N-type dopant such as PH_3 of about 2×10^{-3} percent of the deposition atmosphere. Finally, the metal layers are deposited by evaporation or RF sputtering or other suitable methods.

A solar cell fabricated in accordance with the previous description exhibits overall cell voltages which are slightly less than the sum of the voltages from the individual active layers. The difference in voltage is probably due to the filtering and absorption of sunlight passing through each successive hydrogenated amorphous silicon layer.

The invention will be further illustrated by the following Examples, but it is to be understood that the invention is not meant to be limited solely to the details described therein. Modifications which would be obvious to one of ordinary skill in the solar cell art are contemplated to be within the scope of the invention.

EXAMPLE I

A low sodium content glas about 1/16" thick was coated with about 58 nanometers of transparent conductive oxide (TCO), indium tin oxide, by RF sputtering at a pressure of about 1×10^{-2} Torr and subsequently annealed at about 400°C for about 24 hours. The TCO coating has a sheet resistivity of less than about 10 ohms/square (Ω/□). A platinum cermet ($PtSiO_2$) was deposited on the TCO by RF co-sputtering to a thickness of about 11 nanometers. The cermet had a platinum content of from about 10 to about 15 volume percent, an optical transmittance in the visible region of the aperture of about 95 percent and a resistivity of less than about 10^6 ohm-cm at room temperature. The first layer of hydrogenated amorphous silicon having regions of P^+-type, intrinsic, and N^+-type conductivity was deposited on the platinum cermet in accordance with U.K. Application No. 2019647 and U.S. Patent 4162505. The P^+-type region contacts the cermet and the other regions are contiguous to said region as previously recited. The P^+-type and N^+-type regions were about 41 and 45 nanometers thick, respectively. The intrinsic region was about 270 nanometers thick. The sequence was repeated with a $PtSiO_2$ cermet layer as the tunnel layer and a second layer of hydrogenated amorphous silicon having three regions. The second cermet layer had a thickness of about 9 nanometers. The P^+-type, intrinsic, and N^+-type regions were about 32, 500, and 45 nanometers thick, respectively. Finally, a metal film electrode of aluminum was evaporated to a thickness of about 200 nanometers onto the N^+-type region of the second layer.

The stacked cell in a tandem configuration was illuminated with a light having an intensity of one sun. The measured open circuit voltage (V_{oc}) was about 1.21 volts and the short circuit current (J_{sc}) was about 1.71 milliamperes per square centimeter (mA/cm^2).

EXAMPLE II

A tandem junction solar cell was fabricated in accordance with the procedure outlined in Example I; however, a titanium metal layer with a thickness of about 5 nanometers was deposited on the N^+-type region of the first layer of hydrogenated amorphous silicon and before the deposition of the $PtSiO_2$ cermet and the second layer of hydrogenated amorphous silicon. The $PtSiO_2$, P^+ region and N^+ region for both amorphous silicon layers were the same and about 18, 36, and 36 nanometers thick, respectively. The first intrinsic region has a thickness of about 91 nanometers and the second intrinsic region has a thickness of about 500 nanometers. The TCO layer was about 250 nanometers thick and the titanium contact to the second amorphous silicon layer was about 260 nanometers thick.

Upon illumination with a light having an intensity equivalent to one sun, the cell had a V_{oc} of about 1.34 volts and a J_{sc} of about 2.5 mA/cm^2.

EXAMPLE III

A tandem junction solar cell was fabricated in accordance with the procedures outlined in Example I; however, there was no cermet layer or metal layer separating the first and second layers of hydrogenated amorphous silicon. The front cermet was about 15 nanometers thick. The P^+-type and N^+-type regions of both layers were about 45 nanometers thick. The first intrinsic region was about 76 nanometers thick and the second intrinsic region was about 590 nanometers thick. Upon illumination, the cell had a V_{oc} of about 960 mV and a short circuit current of about 1.98 mA/cm^2. The low V_{oc} indicates the presence of a reverse diode formed between the N^+-type region of the first layer and the P^+-type region of the second layer of hydrogenated amorphous silicon.

EXAMPLE IV

A tandem junction solar cell having five layers of hydrogenated amorphous silicon was fabricated in accordance with the procedure outlined in Example I. The thickness of the intrinsic regions increased in each subsequent layer to equalize the currents of each cell. The thicknesses of the intrinsic regions were 45, 45, 53, 68, 383 nanometers, respectively. Upon illumination, the solar cell exhibited a V_{oc} of about 2.4 volts and a J_{sc} of about 0.580 mA/cm^2.

COMPARATIVE EXAMPLE I

A tandem junction solar cell was fabricated in accordance with the procedure outlined in Example I; however, two insulating layers of Si_4N_3 about 2 nanometers thick separated three layers of hydrogenated amorphous silicon. The layers of amorphous silicon had regions of comparable thickness for N^+-type, P^+-type, and intrinsic amorphous silicon of 38 nanometers, 145 nanometers, and 38 nanometers, respectively. The insulating layer was deposited by a glow discharge. Upon illumination, the cell exhibited a V_{oc} of about 200 mV. Although the insulating layer was thin enough to permit the tunneling of electrons therethrough, the solar cell performance does not compare to the open circuit voltage of the previous Examples.

CLAIMS

1 An amorphous silicon solar cell comprising:

an electrically conductive substrate;

an active body having a first major surface ohmically contacting said substrate and a second major surface opposite to said first major surface, wherein said active body comprises a plurality of layers of hydrogenated amorphous silicon having regions of differing conductivity type, each of said layers forming a photovoltaic generator, said layers being arranged in stacked configuration such that the photovoltages from each of said layers is added, and a transparent tunnel junction is between each adjacent pair of layers of hydrogenated amorphous silicon;

a high work function metal cermet contacting said second major surface; and

means for electrically contacting said high work function metal cermet.

2. The amorphous silicon solar cell according to claim 1 wherein said tunnel junction is formed by a layer of material selected from the group consisting of $PtSiO_2$ cermet, nickel, molybdenum, or titanium.

3. The amorphous silicon solar cell according to claim 2 wherein said tunnel junction is formed by a $PtSiO_2$ cermet.

4. The amorphous silicon solar cell according to claim 3 wherein said tunnel junction further incorporates a transparent metal layer.

5. The amorphous silicon solar cell according to claim 1 wherein said plurality of layers is from 2 to 5 layers of hydrogenated amorphous silicon.

6. The amorphous silicon solar cell according to claim 1 wherein the bandgap energy of the hydrogenated amorphous silicon layers is adjusted to taper from the lowest bandgap energy layer which forms the first major surface of the active region to the highest bandgap energy layer which forms the second major surface.

7. The amorphous silicon solar cell according to claim 6 wherein the bandgap energy of the hydrogenated amorphous silicon is adjusted by varying the content of hydrogen incorporated into the hydrogenated amorphous silicon layer.

8. The amorphous silicon solar cell according to claim 1 wherein each of said layers has three regions of differing conductivity type wherein a first region is of P^+-type conductivity, a said second region contiguous to said first region is of intrinsic hydrogenated amorphous silicon, and a third region of N^+-type conductivity is contiguous to said second region.

9. The amorphous silicon solar cell according to claim 8 wherein the first region of a first layer which forms the first major surface contacts a high work function metal cermet layer of the active region contiguous to said region, said third region contacts said tunnel junction and the first region of a second layer contacts said tunnel junction opposite to the third region of the first layer.

10. The amorphous silicon solar cell according to claim 9 further incorporating a thick film nickel cermet disposed between said active body and said electrically conductive substrate.

Upon illumination with a light having an intensity equivalent to one sun, the cell had a V_{oc} of about 1.34 volts and a J_{sc} of about 2.5 mA/cm².

EXAMPLE III

A tandem junction solar cell was fabricated in accordance with the procedures outlined in Example I; however, there was no cermet layer or metal layer separating the first and second layers of hydrogenated amorphous silicon. The front cermet was about 15 nanometers thick. The P^+-type and N^+-type regions of both layers were about 45 nanometers thick. The first intrinsic region was about 76 nanometers thick and the second intrinsic region was about 590 nanometers thick. Upon illumination, the cell had a V_{oc} of about 960 mV and a short circuit current of about 1.98 mA/cm². The low V_{oc} indicates the presence of a reverse diode formed between the N^--type region of the first layer and the P^--type region of the second layer of hydrogenated amorphous silicon.

EXAMPLE IV

A tandem junction solar cell having five layers of hydrogenated amorphous silicon was fabricated in accordance with the procedure outlined in Example I. The thickness of the intrinsic regions increased in each subsequent layer to equalize the currents of each cell. The thicknesses of the intrinsic regions were 45, 45, 53, 68, 383 nanometers, respectively. Upon illumination, the solar cell exhibited a V_{oc} of about 2.4 volts and a J_{sc} of about 0.580 mA/cm².

COMPARATIVE EXAMPLE I

A tandem junction solar cell was fabricated in accordance with the procedure outlined in Example I; however, two insulating layers of Si_4N_3 about 2 nanometers thick separated three layers of hydrogenated amorphous silicon. The layers of amorphous silicon had regions of comparable thickness for N^--type, P^+-type, and intrinsic amorphous silicon of 38 nanometers, 145 nanometers, and 38 nanometers, respectively. The insulating layer was deposited by a glow discharge. Upon illumination, the cell exhibited a V_{oc} of about 200 mV. Although the insulating layer was thin enough to permit the tunneling of electrons therethrough, the solar cell performance does not compare to the open circuit voltage of the previous Examples.

CLAIMS

1 An amorphous silicon solar cell comprising:

an electrically conductive substrate;

an active body having a first major surface ohmically contacting said substrate and a second major surface opposite to said first major surface, wherein said active body comprises a plurality of layers of hydrogenated amorphous silicon having regions of differing conductivity type, each of said layers forming a photovoltaic generator, said layers being arranged in stacked configuration such that the photovoltages from each of said layers is added, and a transparent tunnel junction is between each adjacent pair of layers of hydrogenated amorphous silicon;

a high work function metal cermet contacting said second major surface; and

means for electrically contacting said high work function metal cermet.

2. The amorphous silicon solar cell according to claim 1 wherein said tunnel junction is formed by a layer of material selected from the group consisting of $PtSiO_2$ cermet, nickel, molybdenum, or titanium.

3. The amorphous silicon solar cell according to claim 2 wherein said tunnel junction is formed by a $PtSiO_2$ cermet.

4. The amorphous silicon solar cell according to claim 3 wherein said tunnel junction further incorporates a transparent metal layer.

5. The amorphous silicon solar cell according to claim 1 wherein said plurality of layers is from 2 to 5 layers of hydrogenated amorphous silicon.

6. The amorphous silicon solar cell according to claim 1 wherein the bandgap energy of the hydrogenated amorphous silicon layers is adjusted to taper from the lowest bandgap energy layer which forms the first major surface of the active region to the highest bandgap energy layer which forms the second major surface.

7. The amorphous silicon solar cell according to claim 6 wherein the bandgap energy of the hydrogenated amorphous silicon is adjusted by varying the content of hydrogen incorporated into the hydrogenated amorphous silicon layer.

8. The amorphous silicon solar cell according to claim 1 wherein each of said layers has three regions of differing conductivity type wherein a first region is of P^--type conductivity, a said second region contiguous to said first region is of intrinsic hydrogenated amorphous silicon, and a third region of N^+-type conductivity is contiguous to said second region.

9. The amorphous silicon solar cell according to claim 8 wherein the first region of a first layer which forms the first major surface contacts a high work function metal cermet layer of the active region contiguous to said region, said third region contacts said tunnel junction and the first region of a second layer contacts said tunnel junction opposite to the third region of the first layer.

10. The amorphous silicon solar cell according to claim 9 further incorporating a thick film nickel cermet disposed between said active body and said electrically conductive substrate.

11. The hydrogenated amorphous silicon solar cell according to claim 10 further incorporating a grid electrode on said high work function metal cermet layer.

12. The hydrogenated amorphous silicon solar cell according to claim 11 further incorporating an antireflection layer deposited upon said grid electrode.

13. An amorphous silicon solar cell substantially as hereinbefore described with particular reference to and as shown in Figs. 1 and 2 of the accompanying drawing.

Printed for Her Majesty's Stationery Office
by Burgess & Son (Abingdon) Ltd.—1983.
Published at The Patent Office, 25 Southampton Buildings,
London, WC2A 1AY, from which copies may be obtained.