

SPECIFICATION Solar Battery

The present invention relates to amorphous silicon solar cells.

Photovoltaic devices, i.e., solar cells, are capable of converting solar radiation into usable 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.

A rectifying junction 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 overall performance of the solar cell is maximized by increasing the total number of photons of differing energy and wavelength which are absorbed by the semiconductor material.

We disclose in our United Kingdom Application No. 7942918 filed December 12, 1979, incorporated herein by reference, a tandem junction structure for an improved amorphous silicon solar cell. The structure comprises two or a series of layers of hydrogenated amorphous silicon arranged in a tandem stacked configuration with one optical path and electrically interconnected by a tunnel junction. The layers of hydrogenated amorphous silicon have regions of differing conductivity to provide a built-in electric field in each semiconductor layer. The layers can have the same, or in a preferred embodiment differing, bandgaps to absorb more completely the distribution of photons of different energies in the solar spectrum. Thus this solar cell structure exhibits increased performance through absorption of a greater portion of the solar spectrum. However, a grid electrode is required in large area solar cells to collect the photocurrent. The grid electrode can shield the active region from up to about 10 percent of the available solar radiation. In addition, as the solar cell size and current of the solar cell increase, the complexity of the grid electrode also increases which places a practical limitation on the size of a large area solar cell.

Thus, it would be highly desirable to have a structure which could maximize the absorption of solar radiation of varying wavelengths and energies without the shielding effect and size limitations of the grid electrode.

According to the present invention there is provided an amorphous silicon solar battery

comprising: a transparent substrate having a major surface on which solar radiation is incident and an opposed major surface; a plurality of transparent conductive oxide strips on said opposed major surface; a plurality of tandem-junction, hydrogenated amorphous silicon solar cells fabricated over and electrically contracting a major portion of each of said transparent conductive oxide strips, said solar cells having a plurality of semiconductor layers of hydrogenated amorphous silicon having regions of differing conductivity type wherein said layers are separated by a tunnel junction, the width of said solar cells being maximised but less than a width which would require a grid electrode to withdraw the current generated during operation of the solar cells and means for connecting said solar cells in series.

There is no basic limit to the length of the solar cell strips. The width of the strips is selected so that a grid electrode is not needed to collect the current generated by the solar battery. The bandgap of the hydrogenated amorphous silicon layers of the tandem junction solar cell strips can be varied over a range from about 1.5 eV to about 1.8 eV by adjusting the hydrogen concentration in the hydrogenated amorphous silicon layers. The thickness of the amorphous silicon layers may be adjusted to maximise the efficiency and equalize the current in each layer.

In the Drawing

The Figure illustrates a cross-sectional view of a high voltage solar battery of the invention.

The invention will be more clearly illustrated by referring to the Figure. A high voltage tandem junction series-connected solar battery is depicted as solar battery 10. Solar radiation 100 impinging on the surface of solar battery 10 is a reference point for the incident surface of each layer or region of the solar battery. Solar battery 10 includes a transparent substrate 32 of materials such as ordinary window glass or a borosilicate glass. A plurality of strips 34 of a transparent conductive oxide, TCO, such as indium tin oxide, ITO, or like materials are formed on the substrate 32. The strips 34 form the top electrode for a plurality of series connected tandem junction hydrogenated amorphous silicon solar cells 20, 21, and 22, etc. The TCO strips should be as thin as possible to allow the maximum transmission of solar radiation. However, the thickness should be adjusted to achieve a sheet resistivity of about 100 $\Omega/\square$ or less. Preferably, the sheet resistivity is about 10 $\Omega/\square$. The thickness of the TCO layer can be selected to take advantage of the antireflection properties thereof. Since solar cells 20, 21 and 22 are equivalent, solar cell 20 will be described in detail with the equivalent labeling for solar cells 21 and 22.

Solar cell 20 incorporates a cermet layer 36 which electrically contacts the TCO layer 34. The cermet layer 36 is fabricated from materials such as PtSiO_2 containing from about 7 to about 15

volume percent of platinum and having a thickness of from about 2 to about 10 nanometers. Alternatively, the cermet layer 36 can be fabricated of a dielectric material such as

5 TiO_2 plus a high-work-function metal, as taught in United States Patent No. 4,167,015 to Hanak, and incorporated herein by reference (our British Application 7849182).

10 An active layer 38 of hydrogenated amorphous silicon which is incident to solar radiation is deposited on and electrically contacts the cermet layer 36. The active layer 38 comprises regions 38a, 38b, and 38c of differing conductivity types. A first region 38a is an hydrogenated amorphous

15 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 38b of intrinsic

20 hydrogenated amorphous silicon, having a thickness of from about 30 to about 300 nanometers, is deposited on region 38a. Undoped or intrinsic hydrogenated amorphous silicon has been found to be of slightly N-type conductivity,

25 as reported in our United States Patent 4,064,521 to Carlson, incorporated herein by reference. A region 38c of N^+ -type hydrogenated amorphous silicon, having a thickness of from about 10 to about 40 nanometers, is contiguous

30 to and deposited on region 38b. The preceding preferred thicknesses of the P^+ and the N^+ amorphous silicon layers are for materials made with dopant concentrations of 0.1 percent B_2H_6 in SiH_4 and 0.2 percent PH_3 in SiH_4 , respectively.

35 The dopant concentration in the gas may affect the optimum thickness of these layers.

A second active layer is shown as 42a, b, and c. The second active layer 42 comprises regions 42a, 42b, and 42c of hydrogenated amorphous

40 silicon of differing conductivity type. Region 42a is similar to region 38a and incorporates a suitable P-type dopant. Region 42b is similar to region 38b and region 42c is similar to region 38c. Regions 42a, 42b, and 42c may be

45 deposited at a higher temperature to produce a layer with a lower concentration of hydrogen and a lower bandgap energy than active layer 38. The thickness of the second active layer 42 should be adjusted so that the current produced by said

50 layer is about equal to the current produced by the first active layer 38, since the total current of solar cell 20 will be limited to the lower current of either active layer 38 or 42.

The tandem junction solar cell 20 is not limited

55 to two active layers. The solar cell can obtain a plurality of active layers. Each pair of active layers is separated by tunnel junctions or a cell interconnect layer. Preferably, solar cell 20 has from 2 to 5 active layers wherein each active

60 layer is separated by a tunnel junction or by a cell interconnect layer which functions as a tunnel junction.

A cell interconnect layer 40 is situated between the active semiconductor layers 38 and

65 42. The cell interconnect layer 40 provides a

single electrical path through the first active la

38 and the second active layer 42 to the back contact 44. The cell interconnect layer 40 also permits the transmission of solar radiation which

70 is not absorbed by the active region 38 to the second active region 42 or additional active regions, where additional absorption can occur.

The interconnect layer 40 is from about 2 to about 15 nanometers thick and is comprised of a

75 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 materials which are transparent to solar radiation. Where the tunnel junction comprises a

80 layer of PtSiO_2 cermet and a transparent metal layer, the metal layer is disposed between the cermet and the N type region 38c of the layer 38. If a thin metal layer is used without the cermet, is is preferable to use a high work-function metal

85 such as platinum. The performance of a tandem junction solar cell 20 is degraded if the interconnect layer 40 is an insulator, in spite of the fact that said insulator could be thin enough to permit electrons to tunnel therethrough. The

90 cell interconnect layer functions like a tunnel junction between the active regions 38 and 42.

The interconnect layer 40 can be omitted if region 38c and region 40a incorporate sufficient

95 P-type and N-type conductivity modifiers, respectively, to form a tunnel junction therebetween.

The efficiency of converting light to electricity of a hydrogenated amorphous silicon solar cell of the above structure approaches a constant when

100 the intrinsic region is about 500 nanometers thick. In a tandem junction structure, any additional thickness of this region only serves to increase the absorption of solar radiation without an increase in cell performance, and robs any

105 subsequent layers of solar radiation. Therefore, the thickness of each intrinsic region should be thinner as the number of stacked hydrogenated amorphous silicon layers increases. In addition, the thickness of each intrinsic region subsequent

110 to the incident intrinsic region should be thicker than the previous region.

The back contact 44, which can be made of titanium, molybdenum, niobium and like materials, which are adherent to and form a good

115 ohmic contact with region 42c, is deposited on said region. Ohmically contacting the back contact 44 and interconnecting solar cell 20 to the base substrate 34 of solar cell 21 is solar cell

120 interconnection layer 46 of indium, tin, or like materials. Wires 52 and 54 contact layer 34 and 46 respectively to withdraw the current generated during illumination of solar battery 10 by solar radiation 100.

Since solar cells 20, 21, and 22 are connected

125 in series, the current remains constant and the voltage of each cell is cumulative. The addition of the voltages enables the fabrication of a solar cell with any desired voltage for a specific application. The solar cell interconnection layer 46 can be

130 made as small as 0.5 percent of the total device

area. Although the layer 46 in single crystalline materials would create problems with the possible shorting of the solar cell structure 20, this is not a problem with amorphous silicon because the lateral conductivity of the doped layers is so poor that for practical purposes it is non-existent, i.e., the lateral conductivity of the amorphous semiconductor layers is similar to an insulator with the lateral sheet resistivity greater than about 10^{10} ohms per square.

When fabricating solar battery 10, the maximum width of the top electrode and solar cells 20, 21, and 22 is determined by the sheet resistivity of the TCO layer, the short circuit current, J_{sc} , of the individual stacked solar cell strips, and a factor which relates to the power loss from each cell which is acceptable without a shielding grid electrode. A grid electrode is necessary where the power loss factor would be greater than about 0.05 or about 5 percent. The width should be maximized but less than a width which would require a grid electrode to withdraw the current generated during the operation of the solar battery. More specifically, the width is determined according to the following formula

$$W = \sqrt{\frac{3fV_{oc}F}{R_{\square}J_{sc}N}}$$

wherein V_{oc} is the total open circuit voltage of the solar battery, $R_{\square}$ is the sheet resistivity of the incident electrode, F is the fill factor, J_{sc} is the short circuit current density, N is the number of strips in the solar battery, and f is the factor related to the percentage of power lost in the front electrode due to resistive heating. The factor f is usually about 0.01 to about 0.08 and preferably about 0.05. For the purposes of determining the width, it is assumed that only the front electrode, in the Figure electrode 34, is current limiting because the back electrode 44 can be made thick enough so that sheet resistivity is not a consideration.

As an example, for J_{sc} of 3 milliamps/cm², N of 9, $R_{\square}$ of 100 ohms/square, V_{oc} of 12.5, F of 0.6, and f of 0.05 the cell width becomes 0.65 cm. For a gap width of 0.005 cm, which can readily be made available by existing photolithographic techniques, the overall area of the solar battery which is not utilized is about 0.7 percent of the total solar battery area. This is greater than an order of magnitude better than a solar cell structure which requires a grid electrode for collection of the photocurrent. As should be apparent from the formula, as the resistance of the front electrode decreases, the width of the strips can increase without affecting the overall solar battery performance. W may be from about 0.2 cm to about 5.0 cm or from about 0.2 cm to about 2.0 cm. If the width is kept constant, then the solar battery performance increases.

The solar battery may be fabricated by several methods. The substrate is coated with a TCO layer by evaporation or other methods known in

the art such as sputtering or pyrolysis of inorganic or organometallic compounds. A TCO glass coated with ITO can also be purchased prefabricated from, among others, Triplex Glass Co., Ltd., Kings Norton, Birmingham, England. The TCO is coated with a positive photoresist such as Shipley 1350-H. The resist is spun on, dried, and exposed to a light source through a photomask to define the grooves between the strips. The device is placed in an apparatus for aligning the mask which maintains the mask stationary and permits the device to move in the x, y, and z directions and also rotated around the geometric axis perpendicular to the plane of the sample. The apparatus described is known in the art. The pattern is developed in a suitable developer. The grooves are etched in the TCO with a suitable etchant such as 55—58 percent HI at 35°C for ITO.

Thereafter, the cermet layer is fabricated in accordance with the teachings in the previously-mentioned United States Patent No. 4,167,015 to Hanak. The TCO layer and the cermet layer can be selected so as to form a quarter wave antireflection coating, for example, 60 nanometers of TCO and 10 nanometers of TCO.

The hydrogenated amorphous silicon semiconductor layers 38 and 42 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 German OS-2743141 (equivalents US SN 727,659, UK Application 39992/77), and also incorporated herein by reference. Layers 38 and 42 can also be fabricated by an RF deposition system wherein the electrodes or coils are contained within the deposition chamber. Suitable parameters for the RF discharge are an RF power equal to or less than about 0.5 watt per square centimeter (W/cm²), on a target having an area of about 160 centimeters squared, 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 layer 38 or 42 is fabricated with a suitable P-type dopant concentration of boron or other suitable dopants in an amount of from about 0.01 to about one percent with respect to the volume of silane. The N⁺-type region is fabricated with a concentration of N-type dopants such as PH₃ of about 0.1 to one percent of the deposition atmosphere. After the deposition of the active regions, the back electrode 44 is deposited by evaporation or RF sputtering or other suitable methods.

After the application of the back electrode 44, the solar battery is coated with a positive or negative photoresist. The individual cells are defined by exposing the surface of the photoresist through an appropriate photomask, i.e., positive or negative mask, and developing the resist by methods known in the art. The grooves are etched in the back electrode with a suitable etchant such as 1 part HF, 2 parts HNO₃, and 7 parts H₂O for a titanium electrode. The photoresist is stripped and

14
a new layer of photoresist is applied, exposed to light and developed in accordance with the previously recited procedure.

- 5 The active layers and the cermet are etched away down to the TCO layer with a plasma etch in CF_4 —4 percent O_2 atmosphere. The plasma etches quickly through the active regions, but slowly about 10 nm/min. through the cermet. If the cermet film is thicker than about 10 nm, the cermet layer can be etched with a reactive RF sputter etching method in a CF_4 — O_2 or Ar— CF_4 — O_2 atmosphere. The end point of the etching is determined usually by the appearance of clear transparent grooves down to the TCO layer.

- 15 Finally, the photoresist is removed and the device surface is plasma etched to remove all traces of organic molecules prior to the deposition of the series interconnect layer. The series interconnect layer is angle evaporated between the grooves at an angle of about 45° with respect to the surface, perpendicular to the grooves and from the direction which interconnects the back electrode of solar cell 20 to the TCO layer of solar cell 21. The series interconnect layer can also be applied by evaporation of the layer over the entire solar battery surface. Thereafter, the excess material is removed and the grooves are formed with photolithographic techniques described previously. After the photoresist is stripped and wires 52 and 54 are attached by known methods, the back of the solar battery can be encapsulated with a suitable material such as Aplezon W, a product of the James G. Biddle Co., Plymouth Meeting, Pa.

- 35 The invention will be further illustrated by the following Example, 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

- 45 A soda-lime glass substrate about 7.6×7.6 centimeters and about 0.16 centimeter in thickness, having a coating of indium tin oxide with a sheet resistance of about 10 ohms/ $\square$, was coated with a positive photoresist, such as Shipley 1350-H, a product of the Shipley Co., Inc., Newton, Mass., by spin coating at 4000 RPM for 30 seconds, and dried at a temperature of about 75°C for about 1 hour. The photoresist was exposed through a photomask which defined 9 strips 7.6 centimeters long and 0.68 centimeter wide. The photoresist was developed in Shipley Developer and the soluble portion of the photoresist, defining the area between the previously recited strips, was removed. Thereafter, the exposed substrate was immersed in a 55—58 percent hydroiodic solution at 35°C to remove the exposed indium tin oxide, leaving behind indium tin oxide photoresist coated strips having a length of 7.6 centimeters and a width of 0.68 centimeter. The remaining photoresist was

- 65 cleaned from the indium tin oxide strips and a PtSiO_2 cermet, having a metal content of about 12 volume percent platinum, was deposited onto the substrate to a thickness of about 23.5 nanometers by RF sputtering. Thereafter, an active semiconductor layer of hydrogenated amorphous silicon having a P^+ -type region of about 31.8 nanometers thick, an undoped region of about 181.6 nanometers thick, and an N^+ -type region of about 90.8 nanometers thick was deposited on the PtSiO_2 cermet. The hydrogenated amorphous silicon layer was formed by RF capacitive glow discharge of silane for the undoped layer and diborane gas in a concentration of about 0.1 volume percent for the P^+ -type region, and PH_3 gas in a concentration of about 0.2 volume percent for the N^+ -type region, the concentrations being with respect to silane.

- A second PtSiO_2 cermet layer having a thickness of about 10.5 nanometers with a platinum concentration of about 12 volume percent was deposited on the first active region by RF sputtering. Thereafter, a second active semiconductor layer was deposited on said second cermet layer. The second semiconductor layer was fabricated in accordance with the procedure outlined for the first layer and had a P^+ -type region thickness of about 31.8 nanometers, an intrinsic region about 363.2 nanometers contiguous to said P^+ -type region, and an N^+ -type region about 90.8 nanometers contiguous to said intrinsic region. A back electrode of titanium about 200 nanometers thick was deposited by sputtering onto the N^+ -type region of the second active semiconductor layer. Thereafter, the device was coated with positive photoresists and exposed through a photomask to create a pattern which is similar to the strips fabricated in the indium tin oxide layer but displaced from the grooves in said indium tin oxide layer so as to enable the layer series interconnection of the tandem junction solar cell strips. The positive photoresist is Shipley 1350-H, a product of the Shipley Company. The exposed photoresist is developed and the soluble portion defining the grooves is removed with a solvent wash. The structure is then etched in a one part hydrofluoric acid, 2 part HNO_3 , and 7 part water solution to remove the portion of the titanium back electrode which will form the grooves in the device. After etching the titanium, the photoresist was stripped with acetone and another coating of photoresist was applied and developed with the same alignment as the previous coating and developing. The device was placed in a plasma etching machine and the active layers underneath the titanium which had already been removed were etched in a CF_4 atmosphere containing four percent oxygen, i.e., DE-100 Freon purchased from the Scientific Gas Products, Inc., South Plainfield, New Jersey. The plasma etching machine was a device produced by the International Plasma Corporation, IPC-200 Series System, Hayward, California. The conditions used in the plasma etch were an RF power of about

800 watts, a $\text{CF}_4\text{--O}_2$ pressure of between 0.5 to 1 torr, a starting temperature of about 25°C and a final temperature of less than or equal to about 90°C . These parameters resulted in an
 5 amorphous silicon etch rate of about 200 nanometers/minute. The etching is continued through the second active layer and the interconnect cermet tunnel junction, said layer etched at a rate of only about 10 nanometers per
 10 minute down to the indium tin oxide layer. The end point of the etching was determined visually because the substrate with the indium tin oxide appears transparent once the hydrogenated amorphous silicon is removed therefrom.

15 At this point in the fabrication, the device was checked for pinholes by shining a light through the device. The pinholes were covered with Microstop, a product marketed by the Michigan Chrome and Chemical Company, Detroit,
 20 Michigan.

The series interconnect layer of the indium was isotropically evaporated over the titanium layer to a thickness of about 200 nanometers. Thereafter, the device was coated with a positive photoresist,
 25 Shipley 1350-H, and exposed through a photomask which was aligned so as to place the third set of grooves adjacent to the second set of grooves. The excess indium was subsequently removed by etching in a solution comprising one
 30 part concentrated HCl , one part 30 percent H_2O_2 , and 6 parts water by volume. The remaining photoresist and Microstop were removed in an acetone wash, a water wash, a deionized water wash, and finally a drying of the device in an oven
 35 for about 30 minutes to one hour at 100°C .

Shorts and shunts in the device were removed in accordance with the procedures outlined in United States Patent No. 4,166,918, to Hanak et al, and incorporated herein by reference. The
 40 contact wires of a flexible copper wire were attached to the end electrodes with a silver epoxy.

The solar battery was illuminated with a light having an intensity of one sun, i.e., A.M. 1, using a tungsten-halogen projector lamp, such as
 45 Sylvania ELH, 300 watt, 120 volt lamp. The solar battery exhibited an overall open circuit voltage (V_{oc}) of about 12.6 volts, a fill factor (FF) of about 0.56, and a short circuit current (J_{sc}) of about 1.82 ma/cm with an overall efficiency of about
 50 1.42 percent. Upon illumination with a light having an intensity of A.M. 2, the overall efficiency of the cell increased from about 1.42 percent to about 1.45 percent and the fill factor increased from about 0.56 to about 0.57.

55 Claims

1. An amorphous silicon solar battery comprising:
 - (a) a transparent substrate having a major surface one which solar radiation is incident and
 60 an opposed major surface;
 - (b) a plurality of transparent conductive oxide strips on said opposed major surface;
 - (c) a plurality of tandem-junction, hydrogenated amorphous silicon solar cells

65 fabricated over and electrically contacting a major portion of each of said transparent conductive oxide strips, said solar cells having a plurality of semiconductor layers of hydrogenated amorphous silicon having regions of differing
 70 conductivity type wherein said layers are separated by a tunnel junction, the width of said solar cells being maximized but less than a width which would require a grid electrode to withdraw the current generated during operation of the
 75 solar cells and

(d) means for connecting said solar cells in series.

2. Solar battery according to Claim 1, wherein said layers of hydrogenated amorphous silicon each have a region of P type conductivity, a
 80 region of intrinsic amorphous silicon contiguous to said P type region and a region of N type conductivity contiguous to said intrinsic region, the region of P type conductivity being closer to the transparent substrate than the intrinsic and N type regions.

3. A solar battery according to Claim 2 wherein said tunnel junction is formed between the N type region of a preceding layer of amorphous silicon
 90 and the P type region of the subsequent layer of amorphous silicon, the preceding layer being closer to the transparent substrate than the subsequent layer.

4. A solar battery according to Claim 3 wherein
 95 said tunnel junction comprises a layer of Pt-SiO_2 cermet.

5. A solar battery according to Claim 3 or 4 wherein said tunnel junction comprises a layer of Pt-SiO_2 cermet and a transparent metal layer.

6. A solar battery according to Claim 5 wherein
 100 said transparent metal layer is disposed between said cermet and said N type region of the semiconductor layer.

7. A solar battery according to any preceding
 105 Claim, wherein the tandem-junction solar cells have from 2 to 5 of said semiconductor layers.

8. A solar battery according to Claim 7 wherein the energy bandgap of said semiconductor layers decreases from the preceding semiconductor
 110 layer to the, or each, subsequent semiconductor layers.

9. A solar battery according to Claim 7 or 8 wherein the intrinsic region of a said semiconductor layer more remote from the
 115 substrate is thicker than the intrinsic region of a said semiconductor layer less remote from the substrate.

10. A solar battery according to any preceding claim wherein the width of the tandem solar cell
 120 strip is determined according to the following formula:

$$W = \sqrt{\frac{3V_{oc}F}{R_s J_{sc} N}}$$

wherein V_{oc} is the total open circuit voltage of the solar battery, J_{sc} is the short circuit current
 125 density, F is the fill factor, R_s is the sheet



800 watts, a $\text{CF}_4\text{--O}_2$ pressure of between 0.5 to 1 torr, a starting temperature of about 25°C and a final temperature of less than or equal to about 90°C . These parameters resulted in an amorphous silicon etch rate of about 200 nanometers/minute. The etching is continued through the second active layer and the interconnect cermet tunnel junction, said layer etched at a rate of only about 10 nanometers per minute down to the indium tin oxide layer. The end point of the etching was determined visually because the substrate with the indium tin oxide appears transparent once the hydrogenated amorphous silicon is removed therefrom.

At this point in the fabrication, the device was checked for pinholes by shining a light through the device. The pinholes were covered with Microstop, a product marketed by the Michigan Chrome and Chemical Company, Detroit, Michigan.

The series interconnect layer of the indium was isotropically evaporated over the titanium layer to a thickness of about 200 nanometers. Thereafter, the device was coated with a positive photoresist, Shipley 1350-H, and exposed through a photomask which was aligned so as to place the third set of grooves adjacent to the second set of grooves. The excess indium was subsequently removed by etching in a solution comprising one part concentrated HCl , one part 30 percent H_2O_2 , and 6 parts water by volume. The remaining photoresist and Microstop were removed in an acetone wash, a water wash, a deionized water wash, and finally a drying of the device in an oven for about 30 minutes to one hour at 100°C .

Shorts and shunts in the device were removed in accordance with the procedures outlined in United States Patent No. 4,166,918, to Hanak et al, and incorporated herein by reference. The contact wires of a flexible copper wire were attached to the end electrodes with a silver epoxy.

The solar battery was illuminated with a light having an intensity of one sun, i.e., A.M. 1, using a tungsten-halogen projector lamp, such as Sylvania ELH, 300 watt, 120 volt lamp. The solar battery exhibited an overall open circuit voltage (V_{oc}) of about 12.6 volts, a fill factor (FF) of about 0.56, and a short circuit current (J_{sc}) of about 1.82 ma/cm with an overall efficiency of about 1.42 percent. Upon illumination with a light having an intensity of A.M. 2, the overall efficiency of the cell increased from about 1.42 percent to about 1.45 percent and the fill factor increased from about 0.56 to about 0.57.

55 Claims

1. An amorphous silicon solar battery comprising:

(a) a transparent substrate having a major surface one which solar radiation is incident and an opposed major surface;

(b) a plurality of transparent conductive oxide strips on said opposed major surface;

(c) a plurality of tandem-junction, hydrogenated amorphous silicon solar cells

65 fabricated over and electrically contacting a major portion of each of said transparent conductive oxide strips, said solar cells having a plurality of semiconductor layers of hydrogenated amorphous silicon having regions of differing conductivity type wherein said layers are separated by a tunnel junction, the width of said solar cells being maximized but less than a width which would require a grid electrode to withdraw the current generated during operation of the solar cells and

(d) means for connecting said solar cells in series.

2. Solar battery according to Claim 1, wherein said layers of hydrogenated amorphous silicon each have a region of P type conductivity, a region of intrinsic amorphous silicon contiguous to said P type region and a region of N type conductivity contiguous to said intrinsic region, the region of P type conductivity being closer to the transparent substrate than the intrinsic and N type regions.

3. A solar battery according to Claim 2 wherein said tunnel junction is formed between the N type region of a preceding layer of amorphous silicon and the P type region of the subsequent layer of amorphous silicon, the preceding layer being closer to the transparent substrate than the subsequent layer.

4. A solar battery according to Claim 3 wherein said tunnel junction comprises a layer of Pt-SiO_2 cermet.

5. A solar battery according to Claim 3 or 4 wherein said tunnel junction comprises a layer of Pt-SiO_2 cermet and a transparent metal layer.

6. A solar battery according to Claim 5 wherein said transparent metal layer is disposed between said cermet and said N type region of the semiconductor layer.

7. A solar battery according to any preceding Claim, wherein the tandem-junction solar cells have from 2 to 5 of said semiconductor layers.

8. A solar battery according to Claim 7 wherein the energy bandgap of said semiconductor layers decreases from the preceding semiconductor layer to the, or each, subsequent semiconductor layers.

9. A solar battery according to Claim 7 or 8 wherein the intrinsic region of a said semiconductor layer more remote from the substrate is thicker than the intrinsic region of a said semiconductor layer less remote from the substrate.

10. A solar battery according to any preceding claim wherein the width of the tandem solar cell strip is determined according to the following formula:

$$W = \sqrt{\frac{3fV_{oc}F}{R_{\square}J_{sc}N}}$$

wherein V_{oc} is the total open circuit voltage of the solar battery, J_{sc} is the short circuit current density, F is the fill factor, $R_{\square}$ is the sheet

resistivity of the transparent conductive oxide, N is the number of solar cell strips in the solar battery, and f is a factor related to the percentage of power loss in the front electrode and is selected so as to be less than the power loss of a solar cell having a grid electrode due to the shielding effect of said grid electrode.

- 5 11. A solar battery according to Claim 10 wherein W is from about 0.2 cm to about 5.0 cm.
- 10 12. A solar battery according to Claim 11 wherein W is from about 0.2 cm to about 2.0 cm.
13. A solar battery according to any preceding claim wherein said means for connecting said

solar cells in series comprises and electrically conductive material which contacts a side of a said solar cell and contacts a surface of that said solar cell remote from the substrate and contacts the transparent conductive oxide strip of a cell adjacent that said solar cell.

- 20 14. A solar battery according to any preceding claim wherein said means for interconnecting said solar cells in series comprises a metal layer.
- 25 15. A solar battery substantially as hereinbefore described with reference to the accompanying drawing.

Printed for Her Majesty's Stationery Office by the Courier Press, Leamington Spa, 1983. Published by the Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained

