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### Transparent Conducting Layers and Photovoltaic Devices Including the Same

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#### Abstract

Photovoltaic devices having transparent contact layers are described herein.

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## **Background/Summary**

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation of U.S. application Ser. No. 18/027,584, filed Mar. 21, 2023, the United States national phase of international application PCT/US2021/051329, filed on Sep. 21, 2021, and claims the benefit of U.S. Provisional Application 63/081,131, filed on Sep. 21, 2020, each of which is incorporated by reference in the entirety.

### **BACKGROUND**

[0002] The present specification generally relates to transparent conducting layers for photovoltaic devices and, more specifically, to the use of particular combinations of materials and layer parameters to improve the efficiency of photovoltaic devices.

[0003] A photovoltaic device generates electrical power by converting light into electricity using semiconductor materials that exhibit the photovoltaic effect. Certain types of semiconductor material can be difficult to manufacture. For example, some material layers provided on the semiconductor material can have both desirable properties and undesirable properties.

Unfortunately, the manufacturing process necessary to efficiently produce the semiconductor material can enhance the undesirable properties of the other material layers. Accordingly, material layers added to the photovoltaic device with the intent of improving efficiency, can ultimately decrease efficiency.

[0004] Accordingly, a need exists for alternative layer structures for use photovoltaic devices.

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## **Description**

### **BRIEF DESCRIPTION OF THE DRAWINGS**

[0005] FIG. 1 schematically depicts a photovoltaic device according to one or more embodiments shown and described herein;

[0006] FIG. 2 schematically depicts a cross-sectional view along 2-2 of the photovoltaic device of FIG. 1 according to one or more embodiments shown and described herein;

[0007] FIG. 3 schematically depicts a substrate according to one or more embodiments shown and described herein;

[0008] FIG. 4 schematically depicts the transparent conducting layer of the photovoltaic device of FIGS. 1 and 2 according to one or more embodiments shown and described herein; and

[0009] FIG. 5 schematically depicts a cross-sectional view of a tandem photovoltaic device according to one or more embodiments shown and described herein.

### **DETAILED DESCRIPTION**

[0010] Photovoltaic devices can be formed from a stack of functional layers formed over a substrate. One or more of the functional layers can include a thin film of material, i.e., the photovoltaic device can be a thin film photovoltaic device. Thin film photovoltaic devices can include an absorber layer for converting light into charge carriers, and conductive layers for collecting the charge carriers. In some instances, a conducting layer can be formed towards an back

side of the module with respect to the absorber layer. In single junction devices, the conductive layer can be disposed at the back side of the module and can use non-transparent metal layers as constituents. However, such non-transparent layers may be unsuitable for use as a conducting layer disposed between junctions in multi-junction photovoltaic devices or tandem photovoltaic devices. The embodiments provided herein relate to transparent conductive layers and photovoltaic devices including the same. The disclosed transparent conductive layers can improve reliability and durability of current collecting portions of photovoltaic devices, while allowing the use of the photovoltaic devices in applications that require transparency, like windows, skylights, and tandem devices.

[0011] Referring now to FIG. 1, an embodiment of a photovoltaic device **100** is schematically depicted. The photovoltaic device **100** can be configured to receive light and transform light into electrical energy, e.g., photons can be absorbed from the light and transformed into electrical current via the photovoltaic effect. Thus, for sake of discussion and clarity, the photovoltaic device **100** can define a front side **102** configured to face a primary light source such as, for example, the sun. Additionally, the photovoltaic device **100** can also define a back side **104** offset from the front side **102** such as, for example, by a plurality of functional layers of material. It is noted that the term “light” can refer to various wavelengths of the electromagnetic spectrum such as, but not limited to, wavelengths in the ultraviolet (UV), infrared (IR), and visible portions of the electromagnetic spectrum. “Sunlight,” as used herein, refers to light emitted by the sun.

[0012] The photovoltaic device **100** can include a plurality of layers disposed between the front side **102** and the back side **104**. As used herein, the term “layer” refers to a thickness of material provided upon a surface. Each layer can cover all or any portion of an adjacent surface. In some embodiments, the layers of the photovoltaic device **100** can be divided into an array of photovoltaic cells **200**. For example, the photovoltaic device **100** can be scribed according to a plurality of serial scribes **202** and a plurality of parallel scribes **204**. The serial scribes **202** can extend along a length Y of the photovoltaic device **100** and demarcate the photovoltaic cells **200** along the length Y of the photovoltaic device **100**. Neighboring cells of the photovoltaic cells **200** can be serially connected along a width X of the photovoltaic device **100**. In other words, a monolithic interconnect of the neighboring cells **200** can be formed, i.e., adjacent to the serial scribe **202**. The parallel scribes **204** can extend along the width X of the photovoltaic device **100** and demarcate the photovoltaic cells **200** along the width X of the photovoltaic device **100**. Under operations, current **205** can predominantly flow along the width X through the photovoltaic cells **200** serially connected by the serial scribes **202**. Under operations, parallel scribes **204** can limit the ability of current **205** to flow along the length Y. Parallel scribes **204** are optional and can be configured to separate the photovoltaic cells **200** that are connected serially into groups **206** arranged along length Y.

[0013] Referring still to FIG. 1, the parallel scribes **204** can electrically isolate the groups **206** of photovoltaic cells **200** that are connected serially. In some embodiments, the groups **206** of the photovoltaic cells **200** can be connected in parallel such as, for example, via electrical bussing. Optionally, the number of parallel scribes **204** can be configured to limit a maximum current generated by each group **206** of the photovoltaic cells **200**. In some embodiments, the maximum current generated by each group **206** can be less than or equal to about 200 milliamps (mA) such as, for example, less than or equal to about 100 mA in one embodiment, less than or equal to about 75 mA in another embodiment, or less than or equal to about 50 mA in a further embodiment.

[0014] Referring now to FIG. 2, the layers of the photovoltaic device **100** can include a thin film stack provided over a substrate **110**. The substrate **110** can be configured to facilitate the transmission of light into the photovoltaic device **100**. The substrate **110** can be disposed at the front side **102** of the photovoltaic device **100**. Referring collectively to FIGS. 2 and 3, the substrate **110** can have a first surface **112** substantially facing the front side **102** of the photovoltaic device **100** and a second surface **114** substantially facing the back side **104** of the photovoltaic device **100**. One or more layers of material can be disposed between the first surface **112** and the second

surface **114** of the substrate **110**.

[0015] Referring to FIG. 3, the substrate **110** can include a transparent layer **120** having a first surface **122** substantially facing the front side **102** of the photovoltaic device **100** and a second surface **124** substantially facing the back side **104** of the photovoltaic device **100**. In some embodiments, the second surface **124** of the transparent layer **120** can form the second surface **114** of the substrate **110**. The transparent layer **120** can be formed from a substantially transparent material such as, for example, glass. Suitable glass can include soda-lime glass, or any glass with reduced iron content. The transparent layer **120** can have any suitable transmittance range, including about 250 nm to about 1,300 nm in some embodiments. The transparent layer **120** may also have any suitable transmittance percentage, including, for example, more than about 50% in one embodiment, more than about 60% in another embodiment, more than about 70% in yet another embodiment, more than about 80% in a further embodiment, or more than about 85% in still a further embodiment. In one embodiment, transparent layer **120** can be formed from a glass with about 90% transmittance, or more. Optionally, the substrate **110** can include a coating **126** applied to the first surface **122** of the transparent layer **120**. The coating **126** can be configured to interact with light or to improve durability of the substrate **110** such as, but not limited to, an antireflective coating, an antisoiling coating, or a combination thereof.

[0016] Referring again to FIG. 2, the photovoltaic device **100** can include a barrier layer **130** configured to mitigate diffusion of contaminants (e.g., sodium) from the substrate **110**, which could result in degradation or delamination of other layers of the photovoltaic stack. The barrier layer **130** can have a first surface **132** substantially facing the front side **102** of the photovoltaic device **100** and a second surface **134** substantially facing the back side **104** of the photovoltaic device **100**. In some embodiments, the barrier layer **130** can be provided adjacent to the substrate **110**. For example, the first surface **132** of the barrier layer **130** can be provided upon the second surface **114** of the substrate **100**. The phrase “adjacent to,” as used herein, means that two layers are disposed contiguously and without any intervening materials between at least a portion of the layers.

[0017] Generally, the barrier layer **130** can be substantially transparent, thermally stable, with a reduced number of pin holes and having high sodium-blocking capability, and good adhesive properties. Alternatively or additionally, the barrier layer **130** can be configured to apply color suppression to light. The barrier layer **130** can include one or more layers of suitable material, including, but not limited to, tin oxide, silicon dioxide, aluminum-doped silicon oxide, silicon oxide, silicon nitride, or aluminum oxide. The barrier layer **130** can have any suitable thickness bounded by the first surface **132** and the second surface **134**, including, for example, more than about 100 Å in one embodiment, more than about 150 Å in another embodiment, or less than about 200 Å in a further embodiment.

[0018] Referring still to FIG. 2, the photovoltaic device **100** can include a transparent conductive oxide (TCO) layer **140** configured to provide electrical contact to transport charge carriers generated by the photovoltaic device **100**. The TCO layer **140** can have a first surface **142** substantially facing the front side **102** of the photovoltaic device **100** and a second surface **144** substantially facing the back side **104** of the photovoltaic device **100**. In some embodiments, the TCO layer **140** can be provided adjacent to the barrier layer **130**. For example, the first surface **142** of the TCO layer **140** can be provided upon the second surface **134** of the barrier layer **130**. Generally, the TCO layer **140** can be formed from one or more layers of n-type semiconductor material that is substantially transparent and has a wide band gap. Specifically, the wide band gap can have a larger energy value compared to the energy of the photons of the light, which can mitigate undesired absorption of light. The TCO layer **140** can include one or more layers of suitable material, including, but not limited to, tin dioxide, doped tin dioxide (e.g., F—SnO<sub>2</sub>), indium tin oxide, or cadmium stannate (Cd<sub>0.2</sub>SnO<sub>0.8</sub>). In embodiments where the TCO layer **140** comprises cadmium stannate, the cadmium stannate can be provided in a crystalline form. For example, the cadmium stannate can be deposited as a film and then subjected to an annealing

process, which transforms the thin film into a crystallized film.

[0019] The photovoltaic device **100** can include a buffer layer **150** configured to provide an insulating layer between the TCO layer **140** and any adjacent semiconductor layers. The buffer layer **150** can have a first surface **152** substantially facing the front side **102** of the photovoltaic device **100** and a second surface **154** substantially facing the back side **104** of the photovoltaic device **100**. In some embodiments, the buffer layer **150** can be provided adjacent to the TCO layer **140**. For example, the first surface **152** of the buffer layer **150** can be provided upon the second surface **144** of the TCO layer **140**. The buffer layer **150** can include material having higher resistivity than the TCO layer **140**, including, but not limited to, intrinsic tin dioxide, zinc magnesium oxide (e.g.,  $\text{Zn.sub.1-xMg.sub.xO}$ ), silicon dioxide ( $\text{SiO.sub.2}$ ), aluminum oxide ( $\text{Al.sub.2O.sub.3}$ ), aluminum nitride (AlN), zinc tin oxide, zinc oxide, tin silicon oxide, or any combination thereof. In some embodiments, the material of the buffer layer **150** can be configured to substantially match the band gap of an adjacent semiconductor layer (e.g., an absorber). The buffer layer **150** may have any suitable thickness between the first surface **152** and the second surface **154**, including, for example, more than about 100 Å in one embodiment, between about 100 Å and about 800 Å in another embodiment, or between about 150 Å and about 600 Å in a further embodiment.

[0020] Referring still to FIG. 2, the photovoltaic device **100** can include an absorber layer **160** configured to cooperate with another layer and form a p-n junction within the photovoltaic device **100**. Accordingly, absorbed photons of the light can free electron-hole pairs and generate carrier flow, which can yield electrical energy. The absorber layer **160** can have a first surface **162** substantially facing the front side **102** of the photovoltaic device **100** and a second surface **164** substantially facing the back side **104** of the photovoltaic device **100**. A thickness of the absorber layer **160** can be defined between the first surface **162** and the second surface **164**. The thickness of the absorber layer **160** can be between about 0.5 μm to about 10 μm such as, for example, between about 1 μm to about 7 μm in one embodiment, or between about 1.5 μm to about 4 μm in another embodiment.

[0021] According to the embodiments described herein, the absorber layer **160** can be formed from a p-type semiconductor material having an excess of positive charge carriers, i.e., holes or acceptors. The absorber layer **160** can include any suitable p-type semiconductor material such as group II-VI semiconductors such as, for example, cadmium and tellurium. Further examples include, but are not limited to, semiconductor materials comprising cadmium, zinc, tellurium, selenium, or any combination thereof. In some embodiments, the absorber layer **160** can include ternaries of cadmium, selenium and tellurium (e.g.,  $\text{CdSe.sub.xTe.sub.1-x}$ ), or a compound comprising cadmium, selenium, tellurium, and one or more additional element (e.g.,  $\text{CdZnSeTe}$ ). The absorber layer **160** may further comprise one or more dopants. The photovoltaic devices **100** provided herein may include a plurality of absorber materials.

[0022] In embodiments where the absorber layer **160** comprises tellurium and cadmium, the average atomic percent of the tellurium in the absorber layer **160** can be greater than or equal to about 25 atomic percent and less than or equal to about 50 atomic percent such as, for example, greater than about 30 atomic percent and less than about 50 atomic percent in one embodiment, greater than about 40 atomic percent and less than about 50 atomic percent in a further embodiment, or greater than about 47 atomic percent and less than about 50 atomic percent in yet another embodiment. Alternatively or additionally, average atomic percent of the tellurium in the absorber layer **160** can be greater than about 45 atomic percent such as, for example, greater than about 49% in one embodiment. It is noted that the average atomic percent described herein is representative of the entirety of the absorber layer **160**, the atomic percentage of material at a particular location within the absorber layer **160** can be graded through the thickness compared to the overall composition of the absorber layer **160**. For example, the absorber layer **160** can have a graded composition.

[0023] In embodiments where the absorber layer **160** comprises selenium and tellurium, the average atomic percent of the selenium in the absorber layer **160** can be greater than 0 atomic percent and less or equal to than about 25 atomic percent such as, for example, greater than about 1 atomic percent and less than about 20 atomic percent in one embodiment, greater than about 1 atomic percent and less than about 15 atomic percent in another embodiment, or greater than about 1 atomic percent and less than about 8 atomic percent in a further embodiment. It is noted that the concentration of tellurium, selenium, or both can be graded through the thickness of the absorber layer **160**. For example, when the absorber layer **160** comprises a compound including selenium at a mole fraction of  $x$  and tellurium at a mole fraction of  $1-x$  ( $\text{Se.sub.}x\text{Te.sub.}1-x$ ),  $x$  can vary in the absorber layer **160** with distance from the first surface **162** of the absorber layer **160**.

[0024] Referring still to FIG. 2, the absorber layer **160** can be doped with a dopant configured to manipulate the charge carrier concentration. In some embodiments, the absorber layer **160** can be doped with a Group V dopant such as, for example, arsenic, phosphorous, antimony, or a combination thereof. Alternatively or additionally, the absorber layer **160** can be doped with a Group IB dopant such as, for example, copper, silver, gold, or a combination thereof. The total density of the dopant within the absorber layer **160** can be controlled. Moreover, the amount of the dopant can vary with distance from the first surface **162** of the absorber layer **160**.

[0025] According to the embodiments provided herein, the p-n junction can be formed by providing the absorber layer **160** sufficiently close to a portion of the photovoltaic device **100** having an excess of negative charge carriers, i.e., electrons or donors. In some embodiments, the absorber layer **160** can be provided adjacent to n-type semiconductor material. Alternatively, one or more intervening layers can be provided between the absorber layer **160** and n-type semiconductor material. In some embodiments, the absorber layer **160** can be provided adjacent to the buffer layer **150**. For example, the first surface **162** of the absorber layer **160** can be provided upon the second surface **154** of the buffer layer **150**.

[0026] The photovoltaic device **100** can include a back contact layer **170** configured to mitigate undesired alteration of the dopant and to provide electrical contact to the absorber layer **160**. The back contact layer **170** can have a first surface **172** substantially facing the front side **102** of the photovoltaic device **100** and a second surface **174** substantially facing the back side **104** of the photovoltaic device **100**. A thickness of the back contact layer **170** can be defined between the first surface **172** and the second surface **174**. The thickness of the back contact layer **170** can be between about 5 nm to about 200 nm such as, for example, between about 10 nm to about 50 nm in one embodiment.

[0027] In some embodiments, the back contact layer **170** can be provided adjacent to the absorber layer **160**. For example, the first surface **172** of the back contact layer **170** can be provided upon the second surface **164** of the absorber layer **160**. In some embodiments, the back contact layer **170** can include combinations of materials from Groups I, II, VI, such as for example, one or more layers containing zinc and tellurium in various compositions. Further exemplary materials include, but are not limited to, a bilayer of cadmium zinc telluride and zinc telluride, or zinc telluride doped with a group V dopant such as, for example, nitrogen. A thin film junction **176** can be defined as the thin film stack primarily contributing to the photovoltaic effect. For example, in some embodiments, the thin film junction **176** can include the transparent conductive oxide layer **140**, the buffer layer **150**, the absorber layer **160**, the back contact layer **170**, or combinations thereof.

[0028] Referring collectively to FIGS. 2, and 4, the photovoltaic device **100** can include a transparent conducting layer **180** configured to provide electrical contact with the back contact layer **170**, the absorber layer **160**, or both. The transparent conducting layer **180** can have a first surface **182** substantially facing the front side **102** of the photovoltaic device **100** and a second surface **184** substantially facing the back side **104** of the photovoltaic device **100**. In some embodiments, the transparent conducting layer **180** can be provided adjacent to the back contact layer **170** or the absorber layer **160**. For example, the first surface **182** of the transparent conducting

layer **180** can be provided upon the second surface **174** of the back contact layer **170** or the second surface **162** of the absorber layer **160**. A thickness of the transparent conducting layer **180** can be defined between the first surface **182** and the second surface **184**. The thickness of the transparent conducting layer **180** can be less than about 500 nm such as, for example, between about 40 nm and about 400 nm in one embodiment, or between about 60 nm and about 350 nm.

[0029] According to the embodiments provided herein, the transparent conducting layer **180** can include one or more functional layers of material. In some embodiments, the conducting layer **180** can have an average transmittance greater than about 50% to light having a wavelength between 300 nm and 1300 nm. Optionally, the conducting layer **180** can have an average transmittance greater than about 50% to light having a wavelength 800 nm to 1300 nm such as, for example, greater than about 85% in one embodiment, or greater than about 90% in another embodiment, or greater than about 95% in further embodiment. The transparent conducting layer **180** can include a diffusion barrier layer **210** operable to limit diffusion of metal species into active areas of the cell **200** such as, for example, the absorber layer **160**. Diffusion of metal species into the absorber layer **160** can degrade conversion efficiency of the cell **200**. Such degradation and decreased performance can be particularly associated with hot and/or humid environments. Accordingly, the use of a suitable diffusion barrier **210** can improve performance of the photovoltaic device **100**.

[0030] The diffusion barrier layer **210** can have a first surface **212** substantially facing the front side **102** of the photovoltaic device **100** and a second surface **214** substantially facing the back side **104** of the photovoltaic device **100**. A thickness of the diffusion barrier layer **210** can be defined between the first surface **212** and the second surface **214**. The thickness of the diffusion barrier layer **210** can be less than about 125 nm such as, for example, between about 2 nm and about 100 nm in one embodiment, or between about 5 nm and about 50 nm in another embodiment.

[0031] In some embodiments, the diffusion barrier layer **210** can be provided adjacent to the back contact layer **170**. For example, the first surface **212** of the diffusion barrier layer **210** can be provided upon the second surface **174** of the back contact layer **170**. Thus, in some embodiments, the first surface **182** of the back contact layer **180** can be formed by the first surface **212** of the diffusion barrier layer **210**. Generally, the diffusion barrier layer **210** can be formed by a material with suitable transmittance capable of being doped “+” type. For example, charge densities of greater than about  $1 \times 10^{16} \text{ cm}^{-3}$  can be considered to be “+” type. In some embodiments, the diffusion barrier layer **210** can be doped  $n^+$ . In alternative embodiments, the diffusion barrier layer **210** can be doped  $p^+$ . Although the boundaries are not rigid, a material can be considered  $n$ -type if electron donor carriers are present in the range of about  $1 \times 10^{11} \text{ cm}^{-3}$  to about  $1 \times 10^{16} \text{ cm}^{-3}$ , and  $n^+$  type if donor carrier density is greater than about  $1 \times 10^{16} \text{ cm}^{-3}$ . Similarly, a material is generally considered  $p$ -type if electron acceptor carriers (i.e. “holes”) are present in the range of about  $1 \times 10^{11} \text{ cm}^{-3}$  to about  $1 \times 10^{16} \text{ cm}^{-3}$ , and  $p^+$  type if acceptor carrier density is greater than about  $1 \times 10^{16} \text{ cm}^{-3}$ . The boundaries are not rigid and may overlap because a layer may be  $p^+$  relative to a layer that is  $p$ -type (or  $n^+$  relative to a layer that is  $n$ -type) if the carrier concentration is at least two orders of magnitude (i.e. 100-fold) higher, regardless of the absolute carrier density. Additionally, charge densities of greater than about  $1 \times 10^{18} \text{ cm}^{-3}$  can be considered to be “++” type; and thus a layer of either  $n$ -type or  $p$ -type can be “++” relative to a layer of the same type that is itself “+” relative to yet a third layer, if the ++ layer has a same-type carrier density more than 100 fold that of the + layer.

[0032] Suitable materials for the diffusion barrier layer **210** can include refractory oxy-nitrides such as, for example, titanium oxy-nitrides ( $\text{TiN}_{x}\text{O}_{y}$ ) or molybdenum oxy-nitrides ( $\text{MoN}_{x}\text{O}_{y}$ ). Without being bound to theory, applicant has discovered that oxy-nitrides can exhibit improved optical properties, i.e., increased transmittance, with increased amounts of oxygen in the alloys. However, it is further believed that the electrical conductivity can degrade with the increased oxygen. Another group of materials suitable for use in the transparent diffusion barrier

**310** include are transparent conductive oxides such as, for example, tin oxide ( $\text{SnO}_{2.2}$ ) zinc oxide ( $\text{ZnO}$ ), indium-tin oxide ( $\text{In}_{2-x}\text{Sn}_x\text{O}_3$ ), cadmium oxide ( $\text{CdO}$ ), and cadmium stannate ( $\text{Cd}_{2.2}\text{SnO}_4$ ). These transparent conductive oxides can be doped with impurities such as F, Al, In, Ga, Ti, and others to alter their electrical and optical properties.

[0033] Unexpectedly, it was discovered that cadmium stannate ( $\text{Cd}_{2.2}\text{SnO}_4$ ) demonstrated a superior combination of diffusion-blocking, optical properties, and electrical properties relative to other transparent conductive oxides. It was further discovered that amorphous cadmium stannate can be utilized for the diffusion barrier layer **210**. As used herein, the term “amorphous” refers to a solid that lacks a long range order. Generally, amorphous cadmium stannate can be formed by depositing a layer of material without converting the morphology of the layer via a heat treatment process. For example, the amorphous cadmium stannate can be deposited at relatively low temperatures and without annealing after deposition. In some embodiments, amorphous cadmium stannate can be formed from  $\text{Cd}_x\text{SnO}_{4.4}$  material where  $0.5 \leq x \leq 2$ .

[0034] Referring still to FIGS. 2 and 4, the transparent conducting layer **180** can include a high conductivity layer **220** configured to provide low device series resistance. The high conductivity layer **220** can have a first surface **222** substantially facing the front side **102** of the photovoltaic device **100** and a second surface **224** substantially facing the back side **104** of the photovoltaic device **100**. A thickness of the high conductivity layer **220** can be defined between the first surface **222** and the second surface **224**. The thickness of the high conductivity layer **220** can be less than about 300 nm such as, for example, between about 30 nm and about 300 nm in one embodiment, between about 50 nm and about 250 nm in another embodiment, or between about 100 nm and about 250 nm in a further embodiment.

[0035] In some embodiments, the high conductivity layer **220** can be positioned further away from the absorber layer **160** or the back contact layer **170** relative to the diffusion barrier layer **210**. Accordingly, the diffusion barrier layer **210** can be positioned between the absorber layer **160** and the high conductivity layer **220** or the back contact layer **170** and the high conductivity layer **220**. Specifically, in some embodiments, the high conductivity layer **220** can be provided adjacent to the high-conductivity layer. For example, the first surface **222** of the high conductivity layer **220** can be provided upon the second surface **214** of the diffusion barrier layer **210**. Generally, the high conductivity layer **220** can be formed by a material with suitable transmittance capable of being doped “++” type. In some embodiments, the diffusion barrier layer **210** can be doped  $n^{++}$ . Accordingly, the high conductivity layer **220** can include a degeneratively doped transparent conductive oxide. In some embodiments, the high conductivity layer **220** can be doped  $n^{++}$  intrinsically or with an oxide dopant. Suitable oxide dopants include, but are not limited to,  $\text{In}_{2.0}\text{O}_{3.3}$ ,  $\text{Ga}_{2.0}\text{O}_{3.3}$ ,  $\text{TiO}_{2.2}$ ,  $\text{Dy}_{2.0}\text{O}_{3.3}$ ,  $\text{SnO}_{2.2}$ ,  $\text{Y}_{2.0}\text{O}_{3.3}$ ,  $\text{Al}_{2.0}\text{O}_{3.3}$ , or any combination thereof. Applicants discovered that cadmium oxide ( $\text{CdO}$ ) such as, for example, indium oxide doped cadmium oxide ( $\text{CdO}:\text{In}_{2.0}\text{O}_{3.3}$ ) or gallium oxide doped cadmium oxide ( $\text{CdO}:\text{Ga}_{2.0}\text{O}_{3.3}$ ) had relatively high electrical mobility compared to other transparent conductive oxides of suitable optical properties. Accordingly, embodiments of the high conductivity layer **220** including cadmium oxide demonstrated a relatively high fill factor, and improved photovoltaic performance.

[0036] According to the embodiments provided herein, the transparent conducting layer **180** can include a capping layer **230** operable to mitigate corrosion of the high conductivity layer **220** in hot and humid environments. The capping layer **230** can have a first surface **232** substantially facing the front side **102** of the photovoltaic device **100** and a second surface **234** substantially facing the back side **104** of the photovoltaic device **100**. A thickness of the capping layer **230** can be defined between the first surface **232** and the second surface **234**. The thickness of the capping layer **230** can be less than about 125 nm such as, for example, between about 2 nm and about 100 nm in one embodiment, or between about 5 nm and about 50 nm in another embodiment.

[0037] In some embodiments, the capping layer **230** can be positioned further away from the



absorber layer **160** or the back contact layer **170** relative to the high conductivity layer **220**.

Accordingly, the high conductivity layer **220** can be positioned between the diffusion barrier layer **210** and the capping layer **230**. Specifically, in some embodiments, the capping layer **230** can be provided adjacent to the high conductivity layer **220**. For example, the first surface **232** of the capping layer **230** can be provided upon the second surface **224** of the high conductivity layer **220**. The capping layer **230** can include a transparent conductive oxide, such as, for example, cadmium stannate. In some embodiments, the capping layer can include amorphous cadmium stannate.

[0038] Referring again to FIG. 2, the photovoltaic device **100** can include a back support **190** configured to cooperate with the substrate **110** to form a housing for the photovoltaic device **100**. The back support **190** can be disposed at the back side **104** of the photovoltaic device **100**. The back support **190** can include any suitable material, including, for example, borosilicate glass, float glass, soda lime glass, carbon fiber, or polycarbonate. Alternatively, the back support **190** may be any suitable material such as a polymer-based back sheet. The back support **190** and substrate **110** can protect the various layers of the photovoltaic device **100** from exposure to moisture and other environmental hazards.

[0039] Referring to FIG. 5, a tandem photovoltaic device **300** is schematically depicted. The tandem photovoltaic device **300** can include a tandem cell **302**, which can be formed via scribing as disclosed above with respect to the photovoltaic cells **200** of the photovoltaic device **100**. The tandem cell **300** can include the thin film junction **176**. The thin film junction **176** can be electrically connected via the transparent conducting layer **180** and, optionally, an electrical bus **236**, to a second junction **310**. As used herein, the phrase “electrically connected” can mean that constituents cooperate to form a substantially ohmic contact directly with one another or indirectly via one or more additional components. Accordingly, current can flow between the second junction **310** and the thin film junction **176** via the electrical connection. In some embodiments, the second junction **310** and the thin film junction **176** can be electrically connected in series. Alternatively, the second junction **310** and the thin film junction **176** can be electrically connected in parallel such as, for example, via one or more additional components or conductors. In some embodiments, the thin film junction **176** can be positioned nearer to the front side **102** of the tandem photovoltaic device **300** than the second junction **310**. The transparent conducting layer **180** can be positioned between the thin film junction **176** and the second junction **310**.

[0040] The second junction **310** can be configured to convert light into electrical energy via the photovoltaic effect. The second junction **310** can include a different semiconductor than the absorber layer **160** of the thin film junction **176** such as, for example, amorphous silicon (a-Si), crystalline silicon (c-Si), or copper indium gallium selenide (CIGS). The thin film junction **176** and the second junction **310** can be configured to absorb different ranges of wavelengths. For example, the thin film junction **176** can be configured to absorb shorter wavelengths of light than the second junction **310**. In some embodiments, the average quantum efficiency between 800 nm and 1,300 nm of the thin film junction **176** can be less than about 20% such as, for example, less than about 10% in one embodiment, or less than about 5% in another embodiment. Additionally, the average quantum efficiency between 800 nm and 1,300 nm of the second junction **310** can be greater than about 50% such as, for example, greater than about 60% in one embodiment, or greater than about 65% in another embodiment.

[0041] It should now be understood that the functional layers of the transparent conducting layer can provide improved transmittance of light, while providing comparable electrical functionality and reliability relative to known non-transparent electrical contacts. Accordingly, the embodiments provided herein can improve the utility of photovoltaic devices. For example, a stack of the diffusion barrier, the high conductivity layer, and the capping layer described herein can be used as a tunnel junction in a tandem photovoltaic device. Alternatively, a stack of the diffusion barrier, the high conductivity layer, and the capping layer described herein can be used as a transparent back electrical contact for a transparent module or for a bifacial module.

[0042] According to embodiments described herein, a tandem photovoltaic device can include a thin film junction, a second junction, and a transparent conducting layer. The thin film junction can include an absorber layer including cadmium and tellurium. The second junction can be electrically connected with the thin film junction. Current can flow between the second junction and the thin film junction. The transparent conducting layer can be disposed between the thin film junction and the second junction. The current can flow through the transparent conducting layer. The transparent conducting layer can include a high conductivity layer and an adjacent layer. The high conductivity layer can include cadmium oxide doped “++” type intrinsically or with an oxide dopant. The adjacent layer that is in contact with the high conductivity layer.

[0043] In another embodiment, a tandem photovoltaic device can include a thin film junction, a second junction, and a transparent conducting layer. The thin film junction can include an absorber layer including cadmium and tellurium. The second junction can be electrically connected with the thin film junction. Current can flow between the second junction and the thin film junction. The transparent conducting layer can be disposed between the thin film junction and the second junction. The current can flow through the transparent conducting layer. The transparent conducting layer can include a high conductivity layer and an adjacent layer. The high conductivity layer can be doped n++. The adjacent layer is in contact with the high conductivity layer. The adjacent layer comprises amorphous cadmium stannate.

[0044] In yet another embodiment, a tandem photovoltaic device can include a thin film junction, a second junction, and a transparent conducting layer. The thin film junction can include an absorber layer including cadmium and tellurium. The second junction can be electrically connected with the thin film junction. Current can flow between the second junction and the thin film junction. The transparent conducting layer can be disposed between the thin film junction and the second junction. The current can flow through the transparent conducting layer. The transparent conducting layer can include amorphous cadmium stannate.

[0045] In a further embodiment, a photovoltaic device can include a thin film junction and a transparent conducting layer. The thin film junction can include an absorber layer including cadmium and tellurium. The transparent conducting layer can form at least a part of a series connection with the thin film junction. The transparent conducting layer can include a high conductivity layer and an adjacent layer. The high conductivity layer can be doped “++” type. The adjacent layer can be in contact with the high conductivity layer.

[0046] In another embodiment, photovoltaic device can include a thin film junction and a transparent conducting layer. The thin film junction can include an absorber layer including cadmium and tellurium. The transparent conducting layer can form at least a part of a series connection with the thin film junction. The transparent conducting layer can include a high conductivity layer and an adjacent layer. The high conductivity layer can include indium oxide doped cadmium oxide. The adjacent layer can be in contact with the high conductivity layer. The adjacent layer can include cadmium stannate.

[0047] In yet another embodiment, a photovoltaic device can include a thin film junction and a transparent conducting layer. The transparent conducting layer can conduct charge carriers from the thin film junction. The transparent conducting layer can include a high conductivity layer and an adjacent layer. The adjacent layer can be in contact with the high conductivity layer. The high conductivity layer comprises indium oxide doped cadmium oxide.

[0048] It is noted that the terms “substantially” and “about” may be utilized herein to represent the inherent degree of uncertainty that may be attributed to any quantitative comparison, value, measurement, or other representation. These terms are also utilized herein to represent the degree by which a quantitative representation may vary from a stated reference without resulting in a change in the basic function of the subject matter at issue.

[0049] While particular embodiments have been illustrated and described herein, it should be understood that various other changes and modifications may be made without departing from the

spirit and scope of the claimed subject matter. Moreover, although various aspects of the claimed subject matter have been described herein, such aspects need not be utilized in combination. It is therefore intended that the appended claims cover all such changes and modifications that are within the scope of the claimed subject matter.

## Claims

1. A photovoltaic device comprising: a thin film junction comprising an absorber layer comprising cadmium and tellurium; and a transparent conducting layer that conducts charge carriers from the thin film junction, wherein: the transparent conducting layer comprises diffusion barrier layer, a high conductivity layer, and a capping layer; the diffusion barrier layer comprises cadmium stannate; the high conductivity layer comprises cadmium oxide; the capping layer comprises cadmium stannate; and the high conductivity layer is between the diffusion barrier layer and the capping layer.
  2. The photovoltaic device of claim 1, wherein at least one of the diffusion barrier layer or the capping layer comprises amorphous cadmium stannate, wherein the amorphous cadmium stannate is a  $\text{Cd}_{0.5}\text{SnO}_{0.4}$  material, where the value of x is in a range from 0.5 to 2.
  3. The photovoltaic device of claim 1, wherein the cadmium oxide is doped  $n^{++}$  and has a charge density greater than  $1 \times 10^{18} \text{ cm}^{-3}$ .
  4. The photovoltaic device of claim 1, wherein the high conductivity layer comprises: cadmium oxide doped with an oxide dopant, wherein the oxide dopant is selected from one or more of:  $\text{In}_2\text{O}_3$ ,  $\text{Ga}_2\text{O}_3$ ,  $\text{TiO}_2$ ,  $\text{Dy}_2\text{O}_3$ ,  $\text{SnO}_2$ ,  $\text{Y}_2\text{O}_3$ , or  $\text{Al}_2\text{O}_3$ .
  5. The photovoltaic device of claim 1, wherein the diffusion barrier layer comprises amorphous cadmium stannate.
  6. The photovoltaic device of claim 1, wherein the high conductivity layer comprises indium oxide doped cadmium oxide.
  7. The photovoltaic device of claim 1, wherein the high conductivity layer comprises gallium oxide doped cadmium oxide.
  8. The photovoltaic device of claim 1, wherein the cadmium oxide is doped  $n^{++}$  with an oxide dopant.
  9. The photovoltaic device of claim 1, wherein the capping layer comprises amorphous cadmium stannate.
  10. The photovoltaic device of claim 1, wherein the absorber layer comprises selenium.
  11. The photovoltaic device of claim 1, wherein the absorber layer comprises zinc.
  12. The photovoltaic device of claim 1, wherein: the thin film junction comprises a back contact layer; and the back contact layer is position between the absorber layer and transparent conducting layer; and the back contact layer comprises zinc and tellurium.
  13. The photovoltaic device of claim 1, wherein the high conductivity layer is thicker than the diffusion barrier layer, and a thickness of the high conductivity layer is less than 300 nm.
  14. A tandem photovoltaic device comprising: a thin film junction comprising an absorber layer comprising cadmium and tellurium; a second junction electrically connected with the thin film junction, whereby current flows between the second junction and the thin film junction; and a transparent conducting layer disposed between the thin film junction and the second junction such that the current flows through the transparent conducting layer, wherein the transparent conducting layer comprises amorphous cadmium stannate.
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