

US Patent & Trademark Office

Patent Public Search | Text View

United States Patent	12389735
Kind Code	B2
Date of Patent	August 12, 2025
Inventor(s)	Wu; Zhao et al.

Stacked photovoltaic device

Abstract

A tandem photovoltaic device includes a perovskite absorbing layer, a crystalline silicon absorbing layer and a single-layer electrical function layer connected in series to the two absorbing layers; a contact interface between the perovskite absorbing layer and the single-layer electrical function layer is a first series interface; and a contact interface between the crystalline silicon absorbing layer and the single-layer electrical function layer is a second series interface; wherein a conducting type at the second series interface is different from a conducting type at the first series interface, and the difference between the work functions is ≥ -0.3 eV and ≤ 0.3 eV.

Inventors:	Wu; Zhao (Shaanxi, CN), Xu; Chen (Shaanxi, CN), Li; Zifeng (Shaanxi, CN), Xie; Junjie (Shaanxi, CN), Liu; Tong (Shaanxi, CN)
Applicant:	LONGI GREEN ENERGY TECHNOLOGY CO., LTD. (Shaanxi, CN)
Family ID:	1000008748501
Assignee:	LONGI GREEN ENERGY TECHNOLOGY CO., LTD. (Shaanxi, CN)
Appl. No.:	18/686581
Filed (or PCT Filed):	May 26, 2022
PCT No.:	PCT/CN2022/095201
PCT Pub. No.:	WO2023/024620
PCT Pub. Date:	March 02, 2023

Prior Publication Data

Document Identifier	Publication Date
US 20240373657 A1	Nov. 07, 2024

Foreign Application Priority Data

Publication Classification**Int. Cl.:** H10K30/84 (20230101); H10K30/57 (20230101)**U.S. Cl.:****CPC** H10K30/84 (20230201); H10K30/57 (20230201);**Field of Classification Search****CPC:** H10K (30/84); H10K (30/57)

References Cited**U.S. PATENT DOCUMENTS**

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
2017/0271622	12/2016	Chaudhari	N/A	N/A
2020/0058819	12/2019	Kirner	N/A	H10F 77/122

FOREIGN PATENT DOCUMENTS

Patent No.	Application Date	Country	CPC
110521008	12/2018	CN	N/A
113257940	12/2020	CN	N/A
2011014635	12/2010	JP	N/A

OTHER PUBLICATIONS

Gong (Highly Efficient Perovskite Solar Cells with Gradient Bilayer Electron Transport Materials), Nano Lett. 2018, 18, 3969-3977 (Year: 2018). cited by examiner

Zheng (Large area efficient interface layer free monolithic perovskite/homo-junction-silicon tandem solar cell with over 20% efficiency), Energy Environ. Sci., 2018, 11, 2432-2443 (Year: 2018). cited by examiner

WIPO, International Search Report for PCT/CN2022/095201, Aug. 10, 2022. cited by applicant

Primary Examiner: Pillay; Devina

Attorney, Agent or Firm: Hodgson Russ LLP

Background/Summary**CROSS-REFERENCE TO RELATED APPLICATIONS**

(1) The present application is a national phase entry under 35 U.S.C. § 371 of International Application No. PCT/CN2022/095201, filed May 26, 2022, which claims priority to Chinese Patent Application No. 202111000183.3, filed Aug. 27, 2021, the entire disclosures of which are incorporated herein in by reference.

TECHNICAL FIELD

(2) The present disclosure relates to the technical field of solar photovoltaic and, more particular, to a tandem photovoltaic device.

BACKGROUND

(3) A two-terminal two-junction tandem structure formed by stacking a wide band gap perovskite device on a crystalline silicon device is adopted by the tandem photovoltaic device, so that the theoretical limit of about 29.4% of power conversion efficiency (PCE) of the crystalline silicon device is anticipated to be broken, and a photovoltaic device with power conversion efficiency exceeding 30% is obtained.

(4) At present, the upper and lower cells of a tandem cell are often connected in series by using multilayer electrical function layers. Although the functions of energy band buffering, carrier transmission and composite series connection are achieved by using this series method, higher parasitic absorption is also caused by using this series method, and the multi-interface superimposed by multilayer electrical function layers may introduce more interface resistance and defect loss, resulting in current loss. In addition, the tandem photovoltaic device is a series stack structure of the crystalline silicon and the perovskite device. The theoretical voltage value should be the sum of the output voltages of the two devices, but the actual situation is that there is a voltage loss so that the actual output voltage is lower than the theoretical voltage.

(5) Therefore, how to reduce the current and voltage loss of the tandem photovoltaic devices is the key to further improve the power conversion efficiency of tandem photovoltaic devices.

SUMMARY

(6) A tandem photovoltaic device is provided by the present disclosure, which aims at reducing the current and voltage loss of the tandem photovoltaic device and further improving the power conversion efficiency of the tandem photovoltaic device.

(7) In a first aspect, a tandem photovoltaic device is provided by the embodiments of the present disclosure, wherein the tandem photovoltaic device includes a perovskite absorbing layer, a crystalline silicon absorbing layer, and a single-layer electrical function layer connected in series to the perovskite absorbing layer and the crystalline silicon absorbing layer; wherein a conducting type of the crystalline silicon absorbing layer at the second series interface is different from a conducting type of the perovskite absorbing layer at the first series interface; and a difference between a work function of the crystalline silicon absorbing layer at the second series interface and a work function of the perovskite absorbing layer at the first series interface is ≥ -0.3 eV and ≤ 0.3 eV.

(8) Optionally, a work function of the single-layer electrical function layer is located within a range between a first work function and a second work function and including the first work function and the second work function; the first work function is a work function of the perovskite absorbing layer at the first series interface on the perovskite absorbing layer; and the second work function is a work function of the crystalline silicon absorbing layer at the second series interface on the crystalline silicon absorbing layer.

(9) Optionally, an electrical conductivity of the single-layer electrical function layer is greater than or equal to a maximum of a first electrical conductivity and a second electrical conductivity; the first electrical conductivity is an electrical conductivity of the perovskite absorbing layer at the first series interface on the perovskite absorbing layer; and the second electrical conductivity is an electrical conductivity of the crystalline silicon absorbing layer at the second series interface on the crystalline silicon absorbing layer.

(10) Optionally, a band gap width of a perovskite material used for the perovskite absorbing layer is 1.5 eV to 2.3 eV.

(11) Optionally, the tandem photovoltaic device further includes at least one of a first interface passivation layer and a second interface passivation layer; a thickness of the first interface passivation layer is less than or equal to 5 nm, and the first interface passivation layer is located between the perovskite absorbing layer and the single-layer electrical function layer; and a

thickness of the second interface passivation layer is less than or equal to 5 nm, and the second interface passivation layer is located between the crystalline silicon absorbing layer and the single-layer electrical function layer.

(12) Optionally, the tandem photovoltaic device further includes a first function layer, a second function layer, a first electrode and a second electrode; the first function layer is located at a side of the perovskite absorbing layer away from the single-layer electrical function layer; and the first electrode is penetrated through or at least partially inserted in the first function layer; and the second function layer is located at a side of the crystalline silicon absorbing layer away from the single-layer electrical function layer; and the second electrode is penetrated through or at least partially inserted in the second function layer.

(13) Optionally, the conducting type of the crystalline silicon absorbing layer at the second series interface is P-type; an N-type perovskite material is used at the first series interface on the perovskite absorbing layer, wherein the N-type perovskite material includes at least one of MAPbBr.sub.3, MAPb.sub.0.91I.sub.2.82, MAPbI.sub.3, FAPbI.sub.3, MASnI.sub.3, MANH.sub.3PbI.sub.3, MASnBr.sub.3, FASnI.sub.3 and CsSnBr.sub.3.

(14) Optionally, an N-type dopant is further employed at the first series interface on the perovskite absorbing layer, wherein the N-type dopant includes at least one of indium, antimony, vanadium and bismuth.

(15) Optionally, a material used for the single-layer electrical function layer includes any one or a doped material of any one of fluorine-doped tin oxide, nickel oxide, copper oxide, molybdenum oxide and 2,2',7,7'-tetrakis[N,N-di(4-methoxyphenyl)amino]-9,9'-spirobifluorene; and the doped material is obtained by doping with any one of an alkali metal element, an alkaline earth metal element, a transition metal element and a halogen metal element.

(16) Optionally, the conducting type of the crystalline silicon absorbing layer at the second series interface is N-type; a P-type perovskite material is used at the first series interface on the perovskite absorbing layer, wherein the P-type perovskite material includes at least one of MAPbBr.sub.3, MAPb.sub.0.91I.sub.2.82, MAPbI.sub.3, FAPbI.sub.3, MASnI.sub.3, MANH.sub.3PbI.sub.3, MASnBr.sub.3, FASnI.sub.3 and CsSnBr.sub.3.

(17) Optionally, a P-type dopant is further employed at the first series interface on the perovskite absorbing layer, wherein the P-type dopant includes at least one of sodium, potassium, copper and oxygen.

(18) Optionally, a material used for the single-layer electrical function layer includes any one or a doped material of any one of zinc oxide, tin oxide, titanium oxide and fullerene carbon; and the doped material is obtained by doping with any one of an alkali metal element, an alkaline earth metal element, a transition metal element and a halogen metal element.

(19) The tandem photovoltaic device provided by the embodiments of the present disclosure includes a perovskite absorbing layer, a crystalline silicon absorbing layer, and a single-layer electrical function layer connected in series to the perovskite absorbing layer and the crystalline silicon absorbing layer, a contact interface between the perovskite absorbing layer and the single-layer electrical function layer is a first series interface, and a contact interface between the crystalline silicon absorbing layer and the single-layer electrical function layer is a second series interface, wherein a conducting type of the crystalline silicon absorbing layer at the second series interface is different from a conducting type of the perovskite absorbing layer at the first series interface; and a difference between a work function of the crystalline silicon absorbing layer at the second series interface and a work function of the perovskite absorbing layer at the first series interface is ≥ -0.3 eV and ≤ 0.3 eV. The difference of the work functions between the perovskite absorbing layer and the crystalline silicon absorbing layer of the tandem photovoltaic device provided by the embodiment of the present disclosure at the contact interface is ≥ -0.3 eV and ≤ 0.3 eV. Therefore, that the work functions between the perovskite absorbing layer and the crystalline silicon absorbing layer are matched may be achieved to avoid the voltage loss caused by the

mismatching of the work functions. Furthermore, based on the matching of the work functions, the energy band structures of the perovskite absorbing layer and the crystalline silicon absorbing layer are matched, without a need to perform energy level buffering. The single-layer electrical function layer may be used to connect the two absorbing layers in series, the parasitic absorption of multi-layer series is reduced. The resistance and interface loss induced by the interfaces between the multi-layers are reduced, and the current and voltage losses are reduced, so that the output voltage of the tandem photovoltaic device is improved, and the power conversion efficiency of the tandem photovoltaic device is further improved.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) In order to more clearly illustrate the technical solutions in the embodiments of the present disclosure, the drawings to be used in the description of the embodiments will be briefly introduced below. Obviously, the drawings in the description below are only some embodiments of the present disclosure. It will be apparent to those skilled in the art to obtain other drawings according to these drawings without involving any inventive effort.

(2) FIG. 1 shows a schematic diagram of a structure of a tandem photovoltaic device according to an embodiment of the present disclosure;

(3) FIG. 2 shows a schematic diagram of work function values and band gap ranges of the crystalline silicon and a part of the perovskite material according to an embodiment of the present disclosure;

(4) FIG. 3a shows a schematic diagram of matching of the energy band structure of a P-type crystalline silicon absorbing layer connected in series to an N-type perovskite absorbing layer according to an embodiment of the present disclosure;

(5) FIG. 3b shows a schematic diagram of matching of the energy band structure of another P-type crystalline silicon absorbing layer connected in series to an N-type perovskite absorbing layer according to an embodiment of the present disclosure;

(6) FIG. 3c shows a schematic diagram of matching of the energy band structure of an N-type crystalline silicon absorbing layer connected in series to a P-type perovskite absorbing layer according to an embodiment of the present disclosure;

(7) FIG. 3d shows a schematic diagram of matching of the energy band structure of another N-type crystalline silicon absorbing layer connected in series to a P-type perovskite absorbing layer according to an embodiment of the present disclosure;

(8) FIG. 4 shows a schematic diagram of a structure of another tandem photovoltaic device according to an embodiment of the present disclosure; and

(9) FIG. 5 shows a schematic diagram of a structure of yet another tandem photovoltaic device according to an embodiment of the present disclosure.

DETAILED DESCRIPTION OF THE EMBODIMENTS

(10) The technical solutions in the embodiments of the application will be described clearly and completely in conjunction with the accompanying drawings in the examples of the application below. Obviously, the described embodiments are only a part of the embodiments of the present application, rather than all of the embodiments. Based on the embodiments in the present disclosure, all other embodiments obtained by a person skilled in the art without involving any inventive effort are within the scope of protection of the present disclosure.

(11) FIG. 1 shows a schematic diagram of a structure of a tandem photovoltaic device according to an embodiment of the present disclosure. With reference to FIG. 1, the tandem photovoltaic device includes a perovskite absorbing layer **12**, a crystalline silicon absorbing layer **13**, and a single-layer electrical function layer **11** connected in series to the perovskite absorbing layer **12** and the

crystalline silicon absorbing layer **13**. A first series interface **121** on the perovskite absorbing layer **12** is a first series interface **121**, and a second series interface **131** on the crystalline silicon absorbing layer **13** is a second series interface **131**; wherein a conducting type of the crystalline silicon absorbing layer **13** at the second series interface **131** is different from a conducting type of the perovskite absorbing layer **12** at the first series interface **121**; and a difference between a work function of the crystalline silicon absorbing layer **13** at the second series interface **131** and a work function of the perovskite absorbing layer **12** at the first series interface **121** is ≥ -0.3 eV and ≤ 0.3 eV.

(12) In the embodiments of the present disclosure, the crystalline silicon absorbing layer **13** and the perovskite absorbing layer **12** are connected in series via the single-layer electrical function layer **11**. Thus, the interface on the perovskite absorbing layer **12** and connected in series to the single-layer electrical function layer **11** is a first series interface **121**, and the interface on the crystalline silicon absorbing layer **13** and connected in series to the single-layer electrical function layer **11** is a second series interface **131**. It is found after studying the tandem photovoltaic device that an energy level p-E.sub.c of the perovskite absorbing layer **12** at the first series interface **121** splits under light conditions to generate an electron quasi-Fermi level of a p-quasi-E.sub.c perovskite absorbing layer and a hole quasi-Fermi level of a p-quasi-E.sub.h perovskite absorbing layer. An energy level s-E.sub.v of the crystalline silicon absorbing layer **13** at the second series interface **131** splits under light conditions to generate an electron quasi-Fermi level of the s-quasi-E.sub.c crystalline silicon absorbing layer and a hole quasi-Fermi level of the s-quasi-E.sub.h crystalline silicon absorbing layer. Under the same material and illumination conditions, the difference p-FS (fermi level splitting) between the p-quasi-E.sub.c and the p-quasi-E.sub.h and the difference s-FS between s-quasi-E.sub.c and s-quasi-E.sub.h are a constant value. At this moment, when the energy level difference of the tandem photovoltaic device $\Delta E = (p\text{-E.sub.c}) - (s\text{-E.sub.v})$, then the open circuit voltage $V_{oc} = (s\text{-quasi-E.sub.e}) - (p\text{-quasi-E.sub.h}) = (p\text{-FS}) + (s\text{-FS}) - \Delta \text{quasi-E} \approx (p\text{-FS}) + (s\text{-FS}) - \Delta E$. Since p-FS and s-FS are fixed values, the magnitude of the V_{oc} is closely related to ΔE . The smaller ΔE is, the larger V_{oc} is. Further, when the work function of the perovskite absorbing layer **12** at the first series interface **121** is mismatched with the work function of the crystalline silicon absorbing layer **13** at the second series interface **131**, ΔE is larger, thus a smaller V_{oc} is resulted in, i.e., the mismatching of the work functions in the tandem photovoltaic device results in a voltage loss. At the same time, when the mismatching of the work functions is large, ΔE is larger. The interface barrier may be generated. It is necessary to introduce multilayer electrical function layers to buffer the carrier energy level and reduce the interface barrier, the thickness of the series structure is increased, the resistivity and transmittance of the intermediate series structure are affected, the parasitic absorption is caused, and current and voltage losses is further led to.

(13) In the embodiment of the present disclosure, in order to avoid the mismatching of the work functions of the two absorbing layers, the work functions of the first series interface **121** and the second series interface **131** may be adjusted. Optionally, since the energy band structure of the crystalline silicon absorbing layer **13** is relatively fixed, the work function of the P-type crystalline silicon is 5.03 eV-5.10 eV, and the work function of the N-type crystalline silicon is 4.42 eV-4.63 eV. Therefore, with the work function of the crystalline silicon material as a reference, the work function of the perovskite absorbing layer **12** at the first series interface **121** may be adjusted so that the difference between the work function of the crystalline silicon absorbing layer **13** at the second series interface **131** and the work function of the perovskite absorbing layer **12** at the first series interface **121** is ≥ -0.3 eV and ≤ 0.3 eV. Thus, the matching of the work functions is realized and the matching of the energy band structures is realized, and then the crystalline silicon absorbing layer **13** and the perovskite absorbing layer **12** may be connected in series by using the single-layer electrical function layer **11**, and the voltage loss from excessive ΔE and small open circuit voltage caused by the work function mismatch may be avoided.

(14) FIG. 2 shows a schematic diagram of work function values and band gap ranges of the

crystalline silicon and a part of the perovskite material according to an embodiment of the present disclosure. As shown in FIG. 2, the ordinate is the energy value, in eV, and the abscissa is the material type, wherein the column corresponding to each material type represents the band gap range, and the values corresponding to the P-type and N-type crystalline silicon materials represent the work function. Thus, the work function of the P-type crystalline silicon in the crystalline silicon is about 5.03 eV, the work function of the N-type crystalline silicon is about 4.45 eV, and the values corresponding to the other perovskite materials respectively represent band edge values of a conduction band and a valence band. The work function of the perovskite material is usually located within the band gap and may be conveniently adjusted. As shown in FIG. 2, in some perovskite materials, the maximum adjustable range of the work function of FAPbI.sub.3 is 4.74 eV-6.24 eV. The maximum adjustable range of the work function of MAPbCl.sub.3 is 4.36 eV-5.93 eV. The maximum adjustable range of the work function of CsPbI.sub.3 is 4.47 eV-6.25 eV. The maximum adjustable range of the work function of CsSnBr.sub.3 is 4.07 eV-5.82 eV, etc. It can be seen that the work function of the crystalline silicon is relatively fixed, while the work function of the perovskite material may be adjusted in a certain range. Taking the work function of the crystalline silicon as a reference, the work function of the perovskite material may be adjusted so as to achieve the matching of the work functions of the crystalline silicon absorbing layer and the perovskite absorbing layer. The work functions shown in FIG. 2 are data when each material exists independently. Since the work functions of each material may change due to the contact in the tandem structure, and at the same time, the work functions of multilayer materials are not easy to be accurately determined, only the values of the work functions when the materials exist independently are considered here. In addition, the type of the perovskite material in FIG. 2 is merely an example, and does not limit the material selection of the perovskite absorbing layer in the embodiment of the present disclosure.

(15) Since the perovskite absorbing layer **12** may have different conducting types and work functions at various places due to different doping element concentrations, types, etc., the crystalline silicon absorbing layer **13** may have different conducting types at various places due to silicon wafer types, doping types, doping positions, etc. Therefore, the conducting type and work function at the first series interface **121** between the perovskite absorbing layer **12** and the single-layer electrical function layer **11** may be regulated, and the conducting type at the second series interface **131** between the crystalline silicon absorbing layer **13** and the single-layer electrical function layer **11** may be regulated. When the work function of the perovskite absorbing layer **12** at the first series interface **121** is regulated, in the range of work functions achievable by different perovskite materials, for example, when the conducting type of the crystalline silicon absorbing layer **13** at the second series interface **131** is P-type, the work function is 5.03 eV. At this moment, the work function of the perovskite absorbing layer **12** at the first series interface **121** may be adjusted to be 5.03 ± 0.3 eV, so that the difference of the work functions is ≥ -0.3 eV and ≤ 0.3 eV. When the conducting type of the crystalline silicon absorbing layer **13** at the second series interface **131** is N-type, the work function is 4.45 eV. At this moment, the work function of the perovskite absorbing layer **12** at the first series interface **121** may be adjusted to be 4.45 ± 0.3 eV, so that the difference of the work functions is ≥ -0.3 eV and ≤ 0.3 eV. The above-mentioned values of the work functions are merely for example, and within the allowable range, a person skilled in the art may select the work functions of the specific crystalline silicon absorbing layer **13** and the perovskite absorbing layer **12** at the contact interface according to requirements. Also, in the perovskite absorbing layer, a bipolar perovskite absorbing layer with the Fermi level located in the middle of the band gap is not included.

(16) FIG. 3a shows a schematic diagram of matching of the energy band structure of a P-type crystalline silicon absorbing layer connected in series to an N-type perovskite absorbing layer according to an embodiment of the present disclosure; FIG. 3b shows a schematic diagram of matching of the energy band structure of another P-type crystalline silicon absorbing layer

connected in series to an N-type perovskite absorbing layer according to an embodiment of the present disclosure; FIG. 3c shows a schematic diagram of matching of the energy band structure of an N-type crystalline silicon absorbing layer connected in series to a P-type perovskite absorbing layer according to an embodiment of the present disclosure; FIG. 3d shows a schematic diagram of matching of the energy band structure of another N-type crystalline silicon absorbing layer connected in series to a P-type perovskite absorbing layer according to an embodiment of the present disclosure. Wherein, the vacuum energy level is 0. When going downwards, the positions of the energy levels include the energy band structures of a single-layer electrical function layer **11**, a perovskite absorbing layer **12** and a crystalline silicon absorbing layer **13**, such as the energy band structures shown in FIGS. 3a and 3c, wherein the single-layer electrical function layer **11** functions in series by realizing a tunneling recombination mechanism at the contact interface with the crystalline silicon absorbing layer **13**. As shown in the energy band structures in FIGS. 3b and 3d, the tunneling recombination occurs at the series interface between the single-layer electrical function layer **11** and the perovskite absorbing layer **12**. Since the electrical conductivity of the crystalline silicon absorbing layer **13** is generally higher than the electrical conductivity of the perovskite absorbing layer **12**, the output effect may be limited by the carrier mobility in the perovskite material as shown in the energy band structure in FIGS. 3b and 3d. In FIGS. 3a, 3b, 3c, 3d, a series effect may be achieved by the single-layer electrical function layer **1** due to that the matching of the energy band structures between the crystalline silicon absorbing layer **13** and the perovskite absorbing layer **12** is achieved.

(17) Optionally, the work function of the single-layer electrical function layer **11** is located within a range between a first work function and a second work function and including the first work function and the second work function.

(18) The first work function is a work function of the perovskite absorbing layer **12** at the first series interface **121** on the perovskite absorbing layer **12**.

(19) The second work function is a work function of the crystalline silicon absorbing layer **13** at the second series interface **131** on the crystalline silicon absorbing layer **13**.

(20) In the embodiments of the present disclosure, the single-layer electrical function layer **11** functions in series between the perovskite absorbing layer **12** and the crystalline silicon absorbing layer **13**. Therefore, a material with a work function located within a range between a first work function and a second work function and including the first work function and the second work function may be selected to be used as the single-layer electrical function layer **11**, wherein the first work function is the work function of the perovskite absorbing layer **12** at the first series interface **121**, and the second work function is the work function of the crystalline silicon absorbing layer **13** at the second series interface **131**. Specifically, when the first work function is 5.03 eV and the second work function is 5.03 ± 0.3 eV, in the case where the specific value of the second work function is greater than the first work function, the upper limit of the value of the work function of the single-layer electrical function layer **11** is the specific value of the second work function, and the lower limit is 5.03 eV. In the case where the specific value of the second work function is less than the first work function, the upper limit of the value of the work function of the single-layer electrical function layer **11** is 5.03 eV, and the lower limit is the specific value of the second work function. The case where the first work function is 4.45 eV and the second work function is 4.45 ± 0.3 eV may be referred to above description, wherein the range of values of the work function of the single-layer electrical function layer **11** includes the end values.

(21) Optionally, the electrical conductivity of the single-layer electrical function layer **11** is greater than or equal to a maximum of a first electrical conductivity and a second electrical conductivity; the first electrical conductivity is an electrical conductivity of the perovskite absorbing layer **12** at the first series interface **121** on the perovskite absorbing layer **12**; and the second electrical conductivity is an electrical conductivity of the crystalline silicon absorbing layer **13** at the second series interface **131** on the crystalline silicon absorbing layer **13**.

(22) In the embodiments of the present disclosure, the electrical conductivity of the single-layer electrical function layer **11** may be greater than or equal to a maximum value of the first electrical conductivity at the position of the contact interface with the crystalline silicon absorbing layer **13** and the second electrical conductivity at the position of the contact interface with the perovskite absorbing layer **12**. Optionally, the electrical conductivity of the material at the contact interface may be determined according to the type, composition, etc. of the material, and the electrical conductivity of the material are regarded as the first electrical conductivity and the second electrical conductivity, the first electrical conductivity and the second electrical conductivity are compared to determine that the electrical conductivity of the single-layer electrical function layer **11** is greater than or equal to the maximum value of the first electrical conductivity and the second electrical conductivity. In practical applications, since the electrical conductivity of the crystalline silicon material is generally higher than the electrical conductivity of the perovskite material, the single-layer electrical function layer **11**, as in the previous FIGS. **3b**, **3d**, is prevented from affecting the contact and transmission capacity of the carriers of the perovskite absorbing layer **12**, the series connection is achieved by a tunneling recombination mechanism at the contact interface between the perovskite absorbing layer and the crystalline silicon absorbing layer **13**.

(23) Optionally, a crystalline silicon material that has light absorption and photo-generated carriers may be separated and collected is used as the crystalline silicon absorbing layer **13**.

(24) In the embodiments of the present disclosure, the crystalline silicon absorbing layer **13** may be used as a lower cell absorbing layer of the tandem photovoltaic device. The crystalline silicon absorbing layer **13** may or may not include a PN junction, and the upper and lower surfaces of the crystalline silicon absorbing layer may have a planar structure, and may also have a light trapping structure, etc. Optionally, a crystalline silicon material that has the effect of light absorption and photo-generated carriers may be separated and collected, such as a crystalline silicon material locally and fully doped on the surface of a silicon wafer may be used as the crystalline silicon absorbing layer **13**, this crystalline silicon material may play a role in light absorption and provide separable photo-generated carriers, and contribute to the power conversion efficiency of the tandem photovoltaic device. However, a microcrystalline silicon or nanocrystalline silicon layer on a passivation layer such as an amorphous silicon, a TOPCon (tunnel oxide passivated contact) cell or the like may absorb incident light, but the generated photo-generated carriers cannot be separated and collected. Therefore, the microcrystalline silicon or nanocrystalline silicon layer on the passivation layer is not used as a material of the single-layer electrical function layer **11**.

(25) Optionally, a band gap width of a perovskite material used for the perovskite absorbing layer **12** is 1.5 eV to 2.3 eV.

(26) In the embodiments of the present disclosure, the perovskite absorbing layer **12** may be used as an upper cell absorbing layer of the tandem photovoltaic device, wherein a wide band gap perovskite material with a band gap width of 1.5 eV-2.3 eV may be used as the perovskite absorbing layer **12**, a single component perovskite material may be used, and a mixed component perovskite material may also be used. A uniform component may be used as the perovskite material in the perovskite absorbing layer **12**, and a non-uniform component may also be used as the perovskite material in the perovskite absorbing layer **12**, so that the work function of the perovskite absorbing layer **12** at the first series interface **121** is complied with the above-mentioned definition. The composition of the perovskite absorbing layer **12** away from the contact interface with the single-layer electrical function layer **11** is not particularly limited in the embodiments of the present disclosure.

(27) Optionally, the conducting type of the crystalline silicon absorbing layer **13** at the second series interface **131** is P-type, and an N-type perovskite material is used at the first series interface **121** on the perovskite absorbing layer **12**, wherein the N-type perovskite material includes at least one of MAPbBr.sub.3, MAPb.sub.0.91I.sub.2.82, MAPbI.sub.3, FAPbI.sub.3, MASnI.sub.3, MANH.sub.3PbI.sub.3, MASnBr.sub.3, FASnI.sub.3 and CsSnBr.sub.3.

(28) In the embodiments of the present disclosure, the conducting type of the crystalline silicon absorbing layer **13** at the second series interface **131** and the conducting type and work function of the perovskite absorbing layer **12** at the first series interface **121** are regulated, and the conducting type and work function at other positions on the crystalline silicon absorbing layer **13** and the perovskite absorbing layer **12** are not limited. For example, when the conducting type at the second series interface **131** is P-type, the conducting type at other positions on the crystalline silicon absorbing layer **13** may be P-type or N-type. For example, N-type doping is performed at the second series interface **131** of the P-type silicon wafer. In a similar way, when the conducting type at the first series interface **121** is P-type, the conducting type at other positions of the perovskite absorbing layer **12** may be P-type or N-type, and the embodiments of the present disclosure do not specifically limit this.

(29) In the embodiments of the present disclosure, when the conducting type at the second series interface **131** is P-type, a single component or two or more mixed components of perovskite materials such as FAPbI.sub.3 , $\text{MAPb.sub.1.1I.sub.3.2}$, $\text{MAPb.sub.1.5Br.sub.4}$, MASnI.sub.3 , $\text{MAPbBr.sub.1.5Cl.sub.1.5}$, MAPbCl.sub.3 , MAPbI.sub.3 , $\text{MAPbI.sub.2.1Cl.sub.0.9}$, FASnI.sub.3 and CsSnI.sub.3 may be used at the first series interface **121**. By adjusting the species and the proportional relationship of various atoms in the perovskite materials, the perovskite absorbing layer **12** is N-type at the first series interface **121**, and the difference between the work function of the perovskite absorbing layer **12** at the first series interface **121** and the work function of the crystalline silicon absorbing layer **13** at the second series interface **131** is ≥ -0.3 eV and ≤ 0.3 eV.

(30) Optionally, an N-type dopant is further employed at the first series interface **121** on the perovskite absorbing layer **12**, wherein the N-type dopant includes at least one of indium, antimony, vanadium and bismuth.

(31) In an embodiment of the present disclosure, an N-type dopant may also be used at the first series interface **121**, so as to better regulate that the first series interface **121** in series is N-type when it is P-type at the second series interface **131**, wherein the N-type dopant may be at least one of indium, antimony, vanadium and bismuth.

(32) The material used for the single-layer electrical function layer **11** includes any one or a doped material of any one of tin oxide, nickel oxide, copper oxide, molybdenum oxide, 2,2',7,7'-tetrakis [N,N-di(4-methoxyphenyl)amino]-9,9'-spirobifluorene, cuprous oxide, tungsten oxide, vanadium oxide, poly[bis(4-phenyl)(2,4,6-trimethylphenyl)amine], cuprous thiocyanate, poly(3,4-ethylene dioxythiophene), poly(3,4-ethylene dioxythiophene)-polystyrene sulfonic acid; and the doped material is obtained by doping with any one of an alkali metal element, an alkaline earth metal element, a transition metal element and a halogen metal element.

(33) In the embodiments of the present disclosure, based on the requirements of parameters such as work function and electrical conductivity, when the second series interface **131** of the crystalline silicon absorbing layer **13** is P-type and the first series interface **121** of the perovskite absorbing layer **12** is N-type, the materials which may be used for the single-layer electrical function layer **11** include any one or a doped material of any one of tin oxide, nickel oxide, copper oxide, molybdenum oxide, 2,2',7,7'-tetrakis[N,N-di(4-methoxyphenyl)amino]-9,9'-spirobifluorene (Spiro-OMeTAD), cuprous oxide, tungsten oxide, vanadium oxide, poly[bis(4-phenyl)(2,4,6-trimethylphenyl)amine] (PTAA), cuprous thiocyanate, poly(3,4-ethylenedioxythiophene) (PEDOT), poly(3,4-ethylene dioxythiophene)-polystyrene sulfonic acid (PEDOT: PSS), wherein the doped material of any one refers to a material obtained by doping any one of tin oxide, nickel oxide, copper oxide, molybdenum oxide, 2,2',7,7'-tetrakis[N,N-di(4-methoxyphenyl)amino]-9,9'-spirobifluorene, cuprous oxide, tungsten oxide, vanadium oxide, poly[bis(4-phenyl)(2,4,6-trimethylphenyl)amine], cuprous thiocyanate, poly(3,4-ethylene dioxythiophene), poly(3,4-ethylene dioxythiophene)-polystyrene sulfonic acid with other elements. Optionally, the doped material may be doped with any one of an alkali metal element, an alkaline earth metal element, a transition metal element and a halogen metal element, such as sodium, calcium, indium, gallium,

fluorine and other elements, and the work functions of the above-mentioned materials are similar. A person skilled in the art may select different types of materials according to process conditions, application requirements, etc., and which is not specifically limited by the embodiments of the present disclosure.

(34) Optionally, the conducting type of the crystalline silicon absorbing layer **13** at the second series interface **131** is N-type, and a P-type perovskite material is used at the first series interface **121** on the perovskite absorbing layer **12**, wherein the P-type perovskite material includes at least one of MAPbBr.sub.3, MAPb.sub.0.91I.sub.2.82, MAPbI.sub.3, FAPbI.sub.3, MASnI.sub.3, MANH.sub.3PbI.sub.3, MASnBr.sub.3, FASnI.sub.3 and CsSnBr.sub.3.

(35) In the embodiments of the present disclosure, when the conducting type at the second series interface **131** is N-type. A single component or two or more mixed components of perovskite materials such as MAPbBr.sub.3, MAPb.sub.0.91I.sub.2.82, MAPbI.sub.3, FAPbI.sub.3, MASnI.sub.3, MANH.sub.3PbI.sub.3, MASnBr.sub.3, FASnI.sub.3 and CsSnBr.sub.3 may be used at the first series interface **121**. The first series interface **121** of the perovskite absorbing layer **12** is P-type by adjusting the species and proportion relationship of various atoms in the perovskite material, and the difference between the work function of the perovskite absorbing layer at first series interface and the work function of the crystalline silicon absorbing layer **13** at the second series interface **131** is ≥ -0.3 eV and ≤ 0.3 eV.

(36) Optionally, a P-type dopant is further employed at the first series interface **121** on the perovskite absorbing layer **12**, wherein the P-type dopant includes at least one of sodium, potassium, copper and oxygen.

(37) In an embodiment of the present disclosure, a P-type dopant may also be used at the first series interface **121**, so as to better regulate that the first series interface **121** in series is P-type when it is N-type at the second series interface **131**, wherein the P-type dopant may be at least one of sodium, potassium, copper and oxygen.

(38) Optionally, the material used for the single-layer electrical function layer **11** includes any one or a doped material of any one of zinc oxide, indium oxide, tin oxide, titanium oxide, molybdenum sulfide, niobium oxide, tantalum oxide, cadmium sulfide, fullerene carbon; and the doped material is obtained by doping with any one of an alkali metal element, an alkaline earth metal element, a transition metal element and a halogen metal element.

(39) In the embodiments of the present disclosure, when the second series interface **131** of the crystalline silicon absorbing layer **13** is N-type and the first series interface **121** of the perovskite absorbing layer **12** is P-type, the material which may be used for the single-layer electrical function layer **11** includes any one or a doped material of any one of zinc oxide, indium oxide, tin oxide, titanium oxide, molybdenum sulfide, niobium oxide, tantalum oxide, cadmium sulfide, fullerene carbon, wherein the doped material of any one refers to a material obtained by doping any one of zinc oxide, indium oxide, tin oxide, titanium oxide, molybdenum sulfide, niobium oxide, tantalum oxide, cadmium sulfide and fullerene carbon with other elements. Optionally, the doped material may be doped with any one of an alkali metal element, an alkaline earth metal element, a transition metal element and a halogen metal element, such as sodium, calcium, indium, gallium, fluorine and other elements, and the work functions of the above-mentioned materials are similar. A person skilled in the art may select different types of materials according to process conditions, application requirements, etc., and which is not specifically limited by the embodiments of the present disclosure.

(40) Optionally, the tandem photovoltaic device further includes a first function layer **14**, a second function layer **15**, a first electrode **16** and a second electrode **17**; and the first function layer **14** is located at a side of the perovskite absorbing layer **12** away from the single-layer electrical function layer **11**; and the first electrode **16** is penetrated through or at least partially inserted in the first function layer **14**.

(41) In the embodiments of the present disclosure, the first function layer **14** may serve as an upper

function layer of the surface of the perovskite absorbing layer **12**, and is located at a side of the perovskite absorbing layer **12** away from the single-layer electrical function layer **11**. The first function layer **14** is a multi-layer structure and may have at least one of functions such as interface passivation, selective contact and transmission, and upper surface anti-reflection. The first electrode **16** may be used as an upper electrode of the surface of the perovskite absorbing layer **12**, wherein the first electrode **16** may be made of a metal or an alloy such as aluminum, copper, silver, etc. Optionally, the first electrode **16** is penetrated through or at least partially inserted in the first function layer **14**. For example, the first electrode **16** may be partially embedded in the first function layer **14**, and may also be penetrated through the first function layer **14**, thus carriers are led out to realize external output.

(42) The second function layer **15** is located at a side of the crystalline silicon absorbing layer **13** away from the single-layer electrical function layer **11**, and the second electrode **17** is penetrated through or at least partially inserted in the second function layer **15**.

(43) In the embodiments of the present disclosure, the second function layer **15** may serve as a lower function layer of the surface of the crystalline silicon absorbing layer **13**, and is located at a side of the crystalline silicon absorbing layer **13** away from the single-layer electrical function layer **11**. The second function layer **15** is a multi-layer structure and may have at least one of functions such as interface passivation, selective contact and transmission, and lower surface anti-reflection. The second electrode **17** may be used as a lower electrode of the surface of the crystalline silicon absorbing layer **13**, wherein the second electrode **17** may be made of a metal or an alloy such as aluminum, copper, silver, etc. Optionally, the second electrode **17** is penetrated through or at least partially inserted in the second function layer **15**. For example, the second electrode **17** may be partially embedded in the second function layer **15**, and may also be penetrated through the second function layer **15**, thus carriers are led out to realize external output.

(44) Optionally, the tandem photovoltaic device further includes at least one of a first interface passivation layer and a second interface passivation layer; the thickness of the first interface passivation layer is less than or equal to 5 nm and the first interface passivation layer is located between the perovskite absorbing layer **12** and the single-layer electrical function layer **11**; and the thickness of the second interface passivation layer is less than or equal to 5 nm, and the second interface passivation layer is located between the crystalline silicon absorbing layer **13** and the single-layer electrical function layer **11**.

(45) In the embodiments of the present disclosure, a first interface passivation layer may be disposed between the perovskite absorbing layer **12** and the single-layer electrical function layer **11**, and/or a second interface passivation layer may be disposed between the crystalline silicon absorbing layer **13** and the single-layer electrical function layer **11**. The material of the first interface passivation layer and the second interface passivation layer may be a dielectric material and have a thickness of less than or equal to 5 nm, so as to avoid excessive thickness affecting the electrical function.

(46) The tandem photovoltaic device provided in the embodiments of the present disclosure includes a perovskite absorbing layer, a crystalline silicon absorbing layer, and a single-layer electrical function layer connected in series to the perovskite absorbing layer and the crystalline silicon absorbing layer, wherein the contact interface between the perovskite absorbing layer and the single-layer electrical function layer is a first series interface, and the contact interface between the crystalline silicon absorbing layer and the single-layer electrical function layer is a second series interface, wherein the conducting type of the crystalline silicon absorbing layer at the second series interface is different from the conducting type of the perovskite absorbing layer at the first series interface; and the difference between the work function of the crystalline silicon absorbing layer at the second series interface and the work function of the perovskite absorbing layer at the first series interface is ≥ -0.3 eV and ≤ 0.3 eV. The difference of the work functions between the perovskite absorbing layer and the crystalline silicon absorbing layer of the tandem photovoltaic

device provided by the embodiment of the present disclosure at the contact interface is ≥ -0.3 eV and ≤ 0.3 eV. Therefore, that the work functions between the perovskite absorbing layer and the crystalline silicon absorbing layer are matched may be achieved to avoid the voltage loss caused by the mismatching of the work functions. Furthermore, based on the matching of the work functions, the energy band structures of the perovskite absorbing layer and the crystalline silicon absorbing layer are matched, without a need to perform energy level buffering. The single-layer electrical function layer may be used to connect the two absorbing layers in series, the parasitic absorption of multi-layer series is reduced. The resistance and interface loss induced by the interfaces between the multi-layers are reduced, and the current and voltage losses are reduced, so that the output voltage of the tandem photovoltaic device is improved, and the power conversion efficiency of the tandem photovoltaic device is further improved.

Embodiment 1

(47) As shown in FIG. 1, the embodiments of the present disclosure provide a specific example of a tandem photovoltaic device, including that: the first series interface **121** of the perovskite absorbing layer **12** is prepared by using a $\text{FAPbI}_{3-x}\text{Br}_x$ single-component perovskite material with a thickness of 300 nm-500 nm, and the first series interface **121** on the perovskite absorbing layer **12** is N-type by using an excessive amount of PbI_2 component during the deposition process; at this moment, the electrical conductivity of the perovskite absorbing layer **12** has the order of 10^{-7} $\text{s}\cdot\text{cm}^{-1}$ much lower than that of crystalline silicon.

(48) A first function layer **14** is disposed on the perovskite absorbing layer **12**. The first function layer **14** has functions of interface passivation, hole selective contact and transmission, and upper surface anti-reflection, wherein the first function layer **14** is a multilayer structure, a calcium fluoride or lithium fluoride material with a thickness of 2 nm is used as an interface passivation layer, a stacked layer of nickel oxide with a thickness of 50 nm and the material of tin oxide with a thickness of 100 nm is used as a hole selective contact and transmission layer, and magnesium fluoride is used as an upper surface anti-reflection thin film.

(49) A P-type silicon wafer is used for the crystalline silicon absorbing layer **13**; a full-layer P-type heavily doped layer is generated at the second series interface **131** on the upper surface of the P-type silicon wafer by using a diffusion or ion implantation method; the doping concentration at the second series interface **131** is $5 \times 10^{18} \text{ cm}^{-3}$, the corresponding resistivity is $4 \times 10^{-2} \Omega\cdot\text{cm}$, and the corresponding electrical conductivity (the reciprocal of the resistivity) is $25 \text{ s}\cdot\text{cm}^{-1}$; and the upper and lower surfaces are in a planar structure.

(50) The lower surface of the crystalline silicon absorbing layer **13** is provided with a second function layer **15**, a passivation contact structure is adopted for the second function layer **15** and functions as interface passivation, electron selective contact and transmission and lower surface anti-reflection, wherein the second function layer **15** is a multilayer structure, respectively being a silicon oxide layer with a thickness of 2 nm, an N-type polycrystalline silicon layer with a thickness of 30 nm, an indium-doped tin oxide layer with a thickness of 100 nm and a silicon nitride thin film stack layer with a thickness of 80 nm.

(51) A single-layer electrical function layer **11** is disposed between the perovskite absorbing layer **12** and the crystalline silicon absorbing layer **13**, wherein the single-layer electrical function layer **11** is an indium tin oxide layer with a thickness of 30 nm; the electrical conductivity of the indium tin oxide may reach $10^4 \text{ s}\cdot\text{cm}^{-1}$, where lightly doped indium oxide is used, with less tin oxide doping, which is below 1 wt %.

(52) The surfaces of the single-layer electrical function layer **11** and the crystalline silicon absorbing layer **13** are provided with an interfacial silicon oxide with a thickness of not more than 2 nm, so as to play a role in surface passivation effect on the crystalline silicon.

(53) The upper surface of the first function layer **14** is provided with a corresponding first electrode **16**, and the lower surface of the second function layer **15** is provided with a corresponding second electrode **17**, wherein the first electrode **16** and the second electrode **17** may be made of metals or

alloys such as aluminum, copper, silver, etc. and be penetrated through or at least partially inserted in the function layer in contact with the first electrode **16** and the second electrode **17**, so as to realize external output.

Embodiment 2

(54) FIG. **4** shows a schematic diagram of a structure of another tandem photovoltaic device according to an embodiment of the present disclosure. As shown in FIG. **4**, a specific example of another tandem photovoltaic device includes: a single-layer electrical function layer **21**, a perovskite absorbing layer **22**, a crystalline silicon absorbing layer **23**, a first function layer **24**, a second function layer **25**, a first electrode **26**, a second electrode **27**, a first interface passivation layer **28** and a second interface passivation layer **29**.

(55) The first series interface **221** of the perovskite absorbing layer **22** is prepared by using an MAPbI.sub.3 single-component perovskite material with a thickness of 300 nm-500 nm, and the first series interface **221** of the perovskite absorbing layer **22** is N-type by using an excessive amount of PbI.sub.2 component during the deposition process; and the resistivity of MAPbI.sub.3 is 4 Ω .cm, and the electrical conductivity is 0.25 s/cm.

(56) A first function layer **24** is disposed on the perovskite absorbing layer **22**. The first function layer **24** has functions of interface passivation, hole selective contact and transmission, and upper surface anti-reflection, wherein the first function layer **24** is a multilayer structure; a calcium fluoride material with a thickness of 2 nm is used as an interface passivation layer; a stacked layer of Spiro-OMeTAD with a thickness of 50 nm and a material of tin oxide with a thickness of 100 nm is used as a hole selective contact and transmission layer; and magnesium fluoride is used as an upper surface anti-reflection thin film.

(57) An N-type silicon wafer is used for the crystalline silicon absorbing layer **23**; a P-type diffusion region is formed by thermal diffusion at the first series interface **231** of the upper surface of the N-type silicon wafer; and both the upper and lower surfaces are of a textured structure, wherein the doping concentration at the first series interface **121** is 1×10^{19} cm⁻³, and the electrical conductivity is 60 s/cm.

(58) The lower surface of the crystalline silicon absorbing layer **23** is provided with a second function layer **25**, a heterojunction structure is adopted for the second function layer and functions as interface passivation, electron selective contact and transmission and lower surface anti-reflection, wherein the second function layer **25** is a multilayer structure, respectively being an intrinsic amorphous silicon with a thickness of 5 nm, an N-type amorphous silicon with a thickness of 20 nm, an indium-doped tin oxide layer with a thickness of 100 nm and a silicon nitride thin film stack layer with a thickness of 80 nm.

(59) A single-layer electrical function layer **21** is disposed between the perovskite absorbing layer **22** and the crystalline silicon absorbing layer **23**; the single-layer electrical function layer **21** is prepared by using an aluminum-doped zinc oxide material and has a thickness of 20 nm; the electrical conductivity of the aluminum-doped zinc oxide layer is generally 100 s/cm.

(60) A first interface passivation layer **28** is disposed between the perovskite absorbing layer **22** and the single-layer electrical function layer **21**, and is made of a material of lithium fluoride with a thickness of 1 nm.

(61) A second interface passivation layer **29** is disposed between the crystalline silicon absorbing layer **23** and the single-layer electrical function layer **21**; a silicon oxide layer with a thickness of 2 nm is used to realize surface passivation on the crystalline silicon.

(62) The upper surface of the first function layer **24** is provided with a corresponding first electrode **26**, and the lower surface of the second function layer **25** is provided with a corresponding second electrode **27**, wherein the first-electrode **26** and the second electrode **27** may be made of metals or alloys such as aluminum, copper, silver, etc. and be penetrated through or at least partially inserted in the function layer in contact with the first electrode **26** and the second electrode **27**, so as to realize external output.

Embodiment 3

(63) FIG. 5 shows a schematic diagram of a structure of yet another tandem photovoltaic device according to an embodiment of the present disclosure. As shown in FIG. 5, a specific example of yet another tandem photovoltaic device includes: a single-layer electrical function layer **31**, a perovskite absorbing layer **32**, a crystalline silicon absorbing layer **33**, a first function layer **34**, a second function layer **35**, a first electrode **36** and a second electrode **37**.

(64) The first series interface **321** of the perovskite absorbing layer **32** is prepared by using a perovskite material with a blend component of $\text{MASnBr}_{0.3}\text{FASnI}_{0.7}$ with a thickness of 300 nm-500 nm; in the deposition process, the first series interface **321** of the perovskite absorbing layer **32** is P-type by using an excessive amount of MAI and FAI components; and the electrical conductivity corresponding to mixed perovskites is of the order of $10^{-3} \text{ s.Math.cm}^{-1}$.

(65) A first function layer **34** is disposed on the perovskite absorbing layer **32**. The first function layer **34** has the functions of selective contact and transmission of electrons and upper surface anti-reflection, wherein the first function layer **34** is a multi-layer structure. A stacked layer of C_{60} with a thickness of 10 nm, tin oxide with a thickness of 20 nm and the material of aluminum-doped tin oxide with a thickness of 80 nm is used as a hole selective contact and transmission layer. Magnesium fluoride is used as an upper surface anti-reflection film.

(66) An N-type silicon wafer is used for the crystalline silicon absorbing layer **33**. The doping concentration is $1 \times 10^{16} \text{ cm}^{-3}$, the electrical conductivity is 2 s.Math.cm^{-1} , and the second series interface **331** of the lower surface of the crystalline silicon absorbing layer **33** is a textured structure and has a P-type region obtained by diffusion or ion implantation doping. The upper surface is a planar structure.

(67) The lower surface of the crystalline silicon absorbing layer **33** is provided with a second function layer **35**. The second function layer **35** and the crystalline silicon absorbing layer **33** form a PERT (passivated emitter rear totally-diffused cell) back surface structure, serving the functions of interface passivation and lower surface anti-reflection. The second function layer **35** is a multilayer structure, respectively being a silicon oxide with a thickness of 3 nm, an aluminum oxide with a thickness of 35 nm and a silicon nitride thin film stack layer with a thickness of 80 nm.

(68) A single-layer electrical function layer **31** is disposed between the perovskite absorbing layer **32** and the crystalline silicon absorbing layer **33** and is made of a nickel oxide material, with a thickness of 50 nm. The electrical conductivity of the un-doped nickel oxide is 5 s.Math.cm^{-1} , meeting the requirement.

(69) The upper surface of the first function layer **34** is provided with a corresponding first electrode **36**, and the lower surface of the second function layer **35** is provided with a corresponding second electrode **37**, wherein the first electrode **36** and the second electrode **37** may be made of metals or alloys such as aluminum, copper, silver, etc. and be penetrated through or at least partially inserted in the function layer in contact with the first electrode **36** and the second electrode **37**, so as to realize external output.

(70) The tandem photovoltaic device provided in the embodiments of the present disclosure is a two-terminal two-junction structure of crystalline silicon and perovskite. The work functions of the perovskite absorbing layer of the upper cell and the crystalline silicon absorbing layer of the lower cell are matched by adjusting the work function of the perovskite absorbing layer of the upper cell at the series interface, thereby the voltage loss at the series interface of the upper and lower cells due to energy level mismatch is reduced. At the same time, since the absorbing layers of the upper and lower cells have a matched work function at the series interface, the intermediate series structure does not need a multi-layer function layer structure for energy band buffering, and a single-layer electrical function layer may realize the series connection of the upper and lower cells, the number of layers of the series structure is reduced, thereby free carrier parasitic absorption caused by the introduction of the multi-layer electrical function layer is reduced, and the quantity of

interfaces is also reduced, thereby the transmission loss caused by interface resistance and defects are reduced.

(71) In summary, the tandem photovoltaic device provided in the present disclosure may effectively reduce the voltage and current loss of the tandem photovoltaic device and improve the overall efficiency of the tandem photovoltaic device by adjusting the matching of the work functions of the absorbing layers of the upper and lower cells at the series interface and using the single-layer electrical function layer serial structure on this basis, and may be applied to upper and lower cells of various structures.

(72) It should be noted that, the term “includes”, “includes” or any other variation thereof herein is intended to cover non-exclusive inclusion, so that a process, method, goods or device that includes a set of elements includes not only those elements but also other elements not explicitly listed, or include elements inherent to the process, method, object, or device. In the absence of further restrictions, the limited element stated by “including a . . . ” does not preclude the existence of another identical element in a process, method, goods or device that includes the element.

(73) The embodiments of the present disclosure have been described above with reference to the accompanying drawings, but the present disclosure is not limited to the specific embodiments described above, which are intended to be illustrative only and not limiting. There are many other forms that may be made by those of ordinary skill in the art, inspired by the present disclosure, without departing from the purposes and the scope protected by claims of the present disclosure, all of which are within the protection of the present disclosure.

Claims

1. A tandem photovoltaic device, wherein the tandem photovoltaic device comprises a perovskite absorbing layer, a crystalline silicon absorbing layer, and a single-layer electrical function layer connected in series to the perovskite absorbing layer and the crystalline silicon absorbing layer, a contact interface between the perovskite absorbing layer and the single-layer electrical function layer is a first series interface, and a contact interface between the crystalline silicon absorbing layer and the single-layer electrical function layer is a second series interface: wherein a conducting type of the crystalline silicon absorbing layer at the second series interface is different from a conducting type of the perovskite absorbing layer at the first series interface; and a difference between a work function of the crystalline silicon absorbing layer at the second series interface and a work function of the perovskite absorbing layer at the first series interface is ≥ -0.3 eV and ≤ 0.3 eV.

2. The tandem photovoltaic device according to claim 1, wherein a work function of the single-layer electrical function layer is located within a range between a first work function and a second work function and including the first work function and the second work function: the first work function is a work function of the perovskite absorbing layer at the first series interface on the perovskite absorbing layer; and the second work function is a work function of the crystalline silicon absorbing layer at the second series interface on the crystalline silicon absorbing layer.

3. The tandem photovoltaic device according to claim 1, wherein an electrical conductivity of the single-layer electrical function layer is greater than or equal to a maximum of a first electrical conductivity and a second electrical conductivity: the first electrical conductivity is an electrical conductivity of the perovskite absorbing layer at the first series interface on the perovskite absorbing layer; and the second electrical conductivity is an electrical conductivity of the crystalline silicon absorbing layer at the second series interface on the crystalline silicon absorbing layer.

4. The tandem photovoltaic device according to claim 1, wherein a band gap width of a perovskite material used for the perovskite absorbing layer is 1.5 eV to 2.3 eV.

5. The tandem photovoltaic device according to claim 1, wherein the tandem photovoltaic device

further comprises at least one of a first interface passivation layer and a second interface passivation layer; a thickness of the first interface passivation layer is less than or equal to 5 nm, and the first interface passivation layer is located between the perovskite absorbing layer and the single-layer electrical function layer; and a thickness of the second interface passivation layer is less than or equal to 5 nm, and the second interface passivation layer is located between the crystalline silicon absorbing layer and the single-layer electrical function layer.

6. The tandem photovoltaic device according to claim 1, wherein the tandem photovoltaic device further comprises a first function layer, a second function layer, a first electrode and a second electrode; the first function layer is located at a side of the perovskite absorbing layer away from the single-layer electrical function layer; and the first electrode is penetrated through or at least partially inserted in the first function layer; and the second function layer is located at a side of the crystalline silicon absorbing layer away from the single-layer electrical function layer; and the second electrode is penetrated through or at least partially inserted in the second function layer.

7. The tandem photovoltaic device according to claim 1, wherein the conducting type of the crystalline silicon absorbing layer at the second series interface is P-type: an N-type perovskite material is used at the first series interface on the perovskite absorbing layer, wherein the perovskite material comprises at least one of FAPbI.sub.3, MAPb.sub.1.1I.sub.3.2, MAPb.sub.1.5Br.sub.4, MASnI.sub.3, MAPbBr.sub.1.5Cl.sub.1.5, MAPbCl.sub.3, MAPbI.sub.3, MAPbI.sub.2.1Cl.sub.0.9, FASnI.sub.3 and CsSnI.sub.3; and an N-type dopant is further employed at the first series interface on the perovskite absorbing layer, wherein the N-type dopant comprises at least one of indium, antimony, vanadium and bismuth.

8. The tandem photovoltaic device according to claim 7, wherein a material used for the single-layer electrical function layer comprises any one or a doped material of any one of tin oxide, nickel oxide, copper oxide, molybdenum oxide, 2,2',7,7'-tetrakis [N,N-di(4-methoxyphenyl)amino]-9,9'-spirobifluorene, cuprous oxide, tungsten oxide, vanadium oxide, poly[bis(4-phenyl) (2,4,6-trimethylphenyl)amine], cuprous thiocyanate, poly(3,4-ethylene dioxy thiophene), poly(3,4-ethylene dioxy thiophene)-polystyrene sulfonic acid; and the doped material is obtained by doping with any one of an alkali metal element, an alkaline earth metal element, a transition metal element and a halogen metal element.

9. The tandem photovoltaic device according to claim 1, wherein the conducting type of the crystalline silicon absorbing layer at the second series interface is N-type: a P-type perovskite material is used at the first series interface on the perovskite absorbing layer, wherein the P-type perovskite material comprises at least one of MAPbBr.sub.3, MAPb.sub.0.91I.sub.2.82, MAPbI.sub.3, FAPbI.sub.3, MASnI.sub.3, MANH.sub.3PbI.sub.3, MASnBr.sub.3, FASnI.sub.3 and CsSnBr.sub.3; and a P-type dopant is further employed at the first series interface on the perovskite absorbing layer, wherein the P-type dopant comprises at least one of sodium, potassium, copper and oxygen.

10. The tandem photovoltaic device according to claim 9, wherein a material used for the single-layer electrical function layer comprises any one or a doped material of any one of zinc oxide, indium oxide, tin oxide, titanium oxide, molybdenum sulfide, niobium oxide, tantalum oxide, cadmium sulfide and fullerene carbon; and the doped material is obtained by doping with any one of an alkali metal element, an alkaline earth metal element, a transition metal element and a halogen metal element.
