

SIMPLIFIED TANDEM STRUCTURE FOR SOLAR CELLS WITH TWO TERMINALS

DESCRIPTION

TECHNICAL FIELD

5 The present invention relates to the field of photovoltaic devices, in particular 2-terminal perovskite tandem type photovoltaic cells on a silicon heterojunction.

 The invention relates to a simplified structure having (photo)electrical properties comparable to those of a conventional tandem structure.

10 PRIOR ART

 Solar cells allow converting a portion of the spectral domain of solar radiation into energy. To increase the yield of this conversion, it is possible to manufacture structures with a tandem architecture comprising two subsets (i.e. a lower cell and an upper cell), absorbing in different spectral domains.

15 Many configurations are possible. For example, the lower cell 10 may be a cell made of perovskite, CIGS ($\text{Cu}(\text{In,Ga})\text{Se}_2$), or it may consist of a silicon-based cell, for example, with a homojunction or with a silicon heterojunction (HET-Si or SHJ standing for “Silicon HeteroJunction solar cell”), of the PERC (“Passivated Emitter and Rear Contact”) or TopCon (“Tunnel Oxide Passivated Contact”) type or an N-type PERT cell with double
20 diffusion of phosphorus.

 For example, the upper cell 30 may be a perovskite, organic or multi-junction cell (MJSC) based on III-V materials (AlGaAs, GaInP, GaAs).

 The two sub-cells are stacked on top of each other according to a NIP/NIP (Figure 1A) or PIN/PIN (Figure 1B) scheme

25 For illustration, in the case of 2-terminal perovskite-type tandem structures on a silicon heterojunction, the NIP-type structure conventionally comprises from the rear face to the front face (Figure 1A):

- a lower cell 10 comprising a layer of n-type doped amorphous silicon 11 ((n) a-Si:H), a substrate of n-type doped crystalline silicon 12 (c-Si(n)) disposed between two layers of intrinsic amorphous silicon 13, 14 ((i) a-Si:H),

- a recombination zone 20,

5 - an upper cell 30 comprising: an N-type layer 33 (SnO₂ for example), an active layer made of a perovskite material 31, a P-type layer 32 (PTAA for example).

Lower and upper electrodes 40, 50 as well as electrical contacts 60, 70 complete the structure.

10 In the case of a PIN-type structure, the P and N type layers are reversed and the structure conventionally comprises from the rear face to the front face (Figure 1B):

15 - a lower cell 10 comprising a layer of P-doped amorphous silicon 15 ((p) a-Si:H), a substrate of n-type doped crystalline silicon 12 (c-Si(n)), disposed between two layers of intrinsic amorphous silicon 13, 14 ((i) a-Si:H), a layer of N-type doped amorphous silicon 11 ((n) a-Si:H),

- a recombination zone 20,

- an upper cell 30 comprising: a P-type layer 32, an active layer made of a perovskite material 31 and an N-type layer 33.

20 Each sub-cell 10, 30 of the tandem structure includes layers which allow separating and selecting the charges according to their polarity.

25 The recombination zone 20 between the two sub-cells is called "recombination junction" because it enables the charges to recombine. It also enables the serial connection of the sub-cells and thus the addition of their voltages. It should lead to the recombination of the electrons generated in the upper cell and the holes generated in the lower cell for a NIP structure tandem (Fig. 1A) and the opposite for a PIN structure (Fig. 1B). For example, the recombination zone 20 is formed of a tunnel junction formed of two highly doped layers: one of the P type 21 ((p+) μ c-Si:H) and the other one of the N type 22 ((n+) μ c-Si:H). In the case of a NIP structure, the layer 21 of the recombination zone also serves as an emitter of the lower cell 10.

However, these tandem structures require many steps to be manufactured, which increases the manufacturing costs and the number of layers and interfaces likely to lower the performances (by adding serial resistance, contact resistances, undesirable recombinations, etc.).

It has been shown that a NIP-like tandem structure comprising a perovskite upper cell and a lower cell based on crystalline silicon and poly-Si could function by directly positioning the upper cell over the lower cell (Shen et al. *"In situ recombination junction between p-Si and TiO₂ enables high-efficiency monolithic perovskite/Si tandem cells"*, Science Advances, 2018; 4: eaau9711). More particularly, a layer of N-type TiO₂ is deposited by ALD directly over the P-doped silicon of the lower cell. Then, a layer of perovskite and a P-type layer made of PTAA are deposited. The operation of this structure is made possible thanks to the low contact resistivity between the ALD layer of TiO₂ and the P-doped silicon of the lower cell.

Similarly, a perovskite tandem structure on a silicon heterojunction has been manufactured by directly depositing the layer of N-type SnO₂ of the upper cell made of perovskite over the P-type layer of the lower cell (Zheng et al. *"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).

However, to date, there is no simplified perovskite tandem structure on a silicon heterojunction based on amorphous silicon and crystalline silicon. Indeed, the amorphous silicon/crystalline silicon heterojunction is very sensitive to the temperature used during the process. In addition, the deposition of the perovskite active layer is generally carried out by liquid means and is therefore greatly dependent on the substrate over which it is deposited as well as the implemented manufacturing steps, which makes a modification of their architecture very difficult to carry out.

DISCLOSURE OF THE INVENTION

The present invention aims to propose a two-terminal perovskite tandem structure on a silicon heterojunction based on amorphous silicon and crystalline

silicon having good electrical properties and which is simpler and less expensive to manufacture.

For this purpose, the present invention provides a structure of 2-terminal perovskite tandem solar cells on a silicon heterojunction based on amorphous silicon and crystalline silicon comprising from the rear face to the front face:

- a first solar cell with a silicon heterojunction based on amorphous silicon and crystalline silicon comprising, from the rear face to the front face: a first layer of a first conductivity type made of amorphous silicon, a substrate of crystalline silicon (of the first conductivity type or of a second conductivity type) disposed between two layers of intrinsic amorphous silicon, and possibly a first layer of a second conductivity type made of amorphous silicon,

- a recombination zone comprising at least one layer based on nanocrystalline or microcrystalline silicon of the second conductivity type,

- a second solar cell comprising an active layer made of a perovskite material and a second layer of a second conductivity type,

the recombination zone further comprising a second layer of the first conductivity type in contact with the active layer of the second cell solar cell or a layer based on nanocrystalline or microcrystalline silicon of the first conductivity type in contact with the active layer of the second solar cell.

The invention differs essentially from the prior art in that in these structures, one of the layers of the recombination zone has a dual function: both the role of charge selection (N or P type contact) and participates in the recombination junction function.

This functional structure enables the recombination of charges and the serial connection between the two sub-cells, without adding an additional layer and/or material between the two sub-cells of the tandem structure, as is the case in conventional tandem structures.

The recombination zone is a fully recombinant P-N junction (regardless of the recombination mechanisms). The recombination zone generates no reverse potential: no voltage drop in the tandem solar cell.

This simplified structure is simpler to manufacture compared to the structures of conventional tandem solar cells. The reduction in the number of structural layers and therefore of steps in the manufacturing process results in a reduction in manufacturing costs.

5 According to a first variant, the first conductivity type is an N-type conductivity (i.e. it is a NIP-type tandem structure).

According to this first variant, the structure may comprise from the rear face to the front face:

10 - the first solar cell with a silicon heterojunction based on amorphous silicon and crystalline silicon comprising from the rear face to the front face: the first layer of the first conductivity type (N type) made of amorphous silicon and the substrate of crystalline silicon disposed between the two layers of intrinsic amorphous silicon,

- the layer based on nanocrystalline or microcrystalline silicon of the second conductivity type (P type),

15 - the second perovskite solar cell comprising towards the front face: the second layer of the first conductivity type (N type), preferably made of SnO_2 , the active layer made of a perovskite material and the second layer of a second conductivity type (P type) preferably made of PTAA.

20 The recombination zone is then formed of the layer based on nanocrystalline or microcrystalline silicon of the second conductivity type (P type) and of the second layer of the first conductivity type (N type). These two layers are in direct contact.

With such an architecture, the upper cell is a conventional cell. This configuration allows obtaining high yields.

25 Alternatively, according to this same first variant, the structure may comprise from the rear face to the front face:

30 - the first solar cell with a silicon heterojunction based on amorphous silicon and crystalline silicon comprising from the rear face to the front face: the first layer of the first conductivity type (N type) made of amorphous silicon and the substrate of crystalline silicon disposed between the two layers of intrinsic amorphous silicon,

- the layer based on nanocrystalline or microcrystalline silicon of the second conductivity type (P type) and the layer based on nanocrystalline or microcrystalline silicon of the first conductivity type (N type),

- the second perovskite solar cell comprising towards the front face: the active layer made of a perovskite material and the second layer of the second conductivity type (P type) preferably made of PTAA.

The recombination zone is then formed of the layer based on nanocrystalline or microcrystalline silicon of the second conductivity type (P type) and of the layer based on nanocrystalline or microcrystalline silicon of the first conductivity type (N type) which form a tunnel junction. The layer based on nanocrystalline or microcrystalline silicon of the first conductivity type (N type) also serves as a charge extractor in the second cell (perovskite). There is no need to add a layer of the first conductivity type (N type), such as an SnO_2 layer, in the second solar cell. The active layer of the second solar cell is in direct contact with the layer based on nanocrystalline or microcrystalline silicon of the first conductivity type (N type).

With this architecture, the layers based on nanocrystalline or microcrystalline silicon may be deposited in the same equipment as the layers made of amorphous silicon of the lower cell and over large surfaces in a homogeneous manner, which simplifies the manufacturing process and facilitates the obtainment of a homogeneous perovskite layer.

According to a second variant, the first conductivity type is a P-type conductivity (i.e. it consists of a PIN-type tandem structure).

According to this second variant, the structure may comprise from the rear face to the front face:

- the first solar cell with a silicon heterojunction based on amorphous silicon and crystalline silicon comprising, from the rear face to the front face: the first layer of the first conductivity type (P type) made of amorphous silicon, the substrate of crystalline silicon disposed between the two layers of intrinsic amorphous silicon, possibly the first layer of the second conductivity type (N type) made of amorphous silicon,

- the layer based on nanocrystalline or microcrystalline silicon of the second conductivity type (N type),

- the second perovskite solar cell comprising towards the front face: the second layer of the first conductivity type (P type), preferably made of PTAA or of TFB or alternatively obtained from phosphonate(s), silanes or carboxylic acids, the active layer made of a perovskite material and the second layer of the second conductivity type (N type), preferably made of SnO_2 or a PCBM/ SnO_2 or PCBM/BCP stack.

The recombination zone is then formed of the layer based on nanocrystalline or microcrystalline silicon of the second conductivity type (N type) and of the second layer of the first conductivity type (P type). These two layers are in direct contact.

With this PIN-type architecture, it is possible to obtain high currents. In addition, the lower cell is a conventional heterojunction cell and needs no more description.

Alternatively, according to this same second variant, the structure may comprise from the rear face to the front face:

- the first solar cell with a silicon heterojunction based on amorphous silicon and crystalline silicon comprising from the rear face to the front face: the first layer of the first conductivity type (P type) made of amorphous silicon, the substrate of crystalline silicon disposed between the two layers of intrinsic amorphous silicon, the first layer of the second conductivity type (N type) made of amorphous silicon,

- the layer based on nanocrystalline or microcrystalline silicon of the second conductivity type (N type) and the layer based on nanocrystalline or microcrystalline silicon of the first conductivity type (P type),

- the second perovskite solar cell comprising towards the front face: the active layer made of a perovskite material and the second layer of the second conductivity type (N type) preferably made of SnO_2 or a PCBM/ SnO_2 or PCBM/BCP stack.

The recombination zone is then formed of the layer based on nanocrystalline or microcrystalline silicon of the second conductivity type (N type) and a layer based on nanocrystalline or microcrystalline silicon of the first conductivity type (P

type) which form a tunnel junction. The layer based on nanocrystalline or microcrystalline silicon of the first conductivity type (P type) also serves as a charge extractor in the perovskite cell. There is no need to add a layer of the first conductivity type (P type), such as a layer of PTAA, in the second solar cell. The active layer of the second solar cell is in direct contact with the layer based on nanocrystalline or microcrystalline silicon of the first conductivity type (P type).

With this architecture, the layers based on nanocrystalline or microcrystalline silicon may be deposited in the same equipment as the layers made of amorphous silicon of the lower cell and over large surfaces in a homogeneous manner, which simplifies the manufacturing process and facilitates the obtainment of a homogeneous perovskite layer. High currents may be obtained with this architecture.

Advantageously, the layer based on nanocrystalline or microcrystalline silicon of the first conductivity type and/or the layer based on nanocrystalline or microcrystalline silicon of the second conductivity type is made of $\mu\text{c-Si:H}$ (p+), $\mu\text{c-Si:H}$ (n+), N or P type nc-SiC_x or N or P type nc-SiO_y with x ranging from 0 to 1 and y ranging from 0 to 2.

By nanocrystalline or microcrystalline, it should be understood a layer including both an amorphous phase and a crystalline phase, the crystalline phase having a grain size smaller than 30 nm. It is generally comprised between 1 and 10 nm for nanocrystalline silicon and generally between 10 and 30 nm and preferably between 10 and 20 nm for microcrystalline. Sometimes, in the literature, for grain sizes smaller than 10 nm, the microcrystalline silicon designation is also found.

Advantageously, the layer based on nanocrystalline or microcrystalline silicon of the first conductivity type and/or the layer based on nanocrystalline or microcrystalline silicon of the second conductivity type has a thickness ranging from 15 nm to 60 nm and preferably from 20 nm to 40 nm.

Advantageously, the layer based on nanocrystalline or microcrystalline silicon of the first conductivity type and/or the layer based on nanocrystalline or microcrystalline silicon of the second conductivity type has a conductivity higher than $10^{-3} \text{ S.cm}^{-1}$.

Advantageously, the layer based on nanocrystalline or microcrystalline silicon of the first conductivity type and/or the layer based on nanocrystalline or microcrystalline silicon of the second conductivity type has a doping level of $10^{18}/\text{cm}^3$ to $10^{22}/\text{cm}^3$, and preferably between $10^{19}/\text{cm}^3$ and $10^{20}/\text{cm}^3$ for the P type and between $10^{20}/\text{cm}^3$ and $10^{21}/\text{cm}^3$ for the N type.

Other features and advantages of the invention will appear from the following complementary description.

It goes without saying that this complementary description is given only for illustration of the object of the invention and should in no way be interpreted as a limitation of this object.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be better understood upon reading the description of embodiments given merely for informative and non-limiting purposes with reference to the appended drawings wherein:

Figure 1A previously described in the prior art represents, schematically and in section, a two-terminal NIP-NIP tandem structure.

Figure 1B previously described in the prior art represents, schematically and in section, a two-terminal PIN-PIN tandem structure.

Figure 2A represents, schematically and in section, a simplified two-terminal NIP-NIP tandem structure, according to a particular embodiment of the invention.

Figure 2B represents, schematically and in section, a simplified two-terminal PIN-PIN tandem structure, according to another particular embodiment of the invention.

Figure 3A represents, schematically and in section, a simplified two-terminal NIP-NIP tandem structure, according to another particular embodiment of the invention.

Figure 3B represents, schematically and in section, a simplified two-terminal PIN-PIN tandem structure, according to another particular embodiment of the invention.

Figures 4A and 4B are graphs representing the EQE and the '1-R_{tot}' value as a function of the wavelength (with R_{tot} corresponding to the total reflection of the stack of the cell (without the metallisation at the front face)), obtained for tandem structures polished at the front face and at the rear face, of the NIP type (corresponding to Figures 1A, 2A and 3A) and of the PIN type (corresponding to Figures 1B, 2B and 3B) respectively.

Figures 5A and 5B are graphs representing the EQE and the '1-R_{tot}' value as a function of the wavelength, obtained for tandem structures whose substrate is polished at the front face and with a classic pyramidal texturing at the rear face, of the NIP type (corresponding to Figures 1B, 2B and 3B) and of the PIN type (corresponding to Figures 1A, 2A and 3A) respectively.

Figures 6A and 6B are graphs representing the EQE and the '1-R_{tot}' value as a function of the wavelength, obtained for textured tandem structures at the front face and at the rear face, of the NIP type (corresponding to Figures 1A, 2A and 3A) and of the PIN type (corresponding to Figures 1B, 2B and 3B) respectively.

The different portions represented in the figures are not necessarily plotted according to a uniform scale, to make the figures more readable.

Furthermore, in the description hereinafter, terms that depend on the orientation, such as "top"/"upper", "bottom"/"lower", etc. of a structure apply while considering that the tandem device and the test structure are oriented as illustrated in the figures.

DETAILED DISCLOSURE OF PARTICULAR EMBODIMENTS

Figures 2A, 2B, 3A and 3B represent four simplified perovskite tandem structures 100 over a silicon heterojunction (amorphous silicon/crystalline silicon). Each of these tandem structures 100 comprises:

- a first cell 110 (or lower cell for “bottom cell”) with a silicon heterojunction (HET-Si or SHJ standing for “Silicon HeteroJunction solar cell”) positioned at the rear face of the device,

- a recombination zone: a completely recombinant P-N junction (regardless of the recombination mechanisms), made without addition of additional layers and/or materials; the recombination zone does not lead to any reverse potential (i.e. no voltage drop in the tandem solar cell),

- a second perovskite cell 130 (or upper cell for “top cell”) positioned at the front face of the device.

The face intended to receive the light radiation (represented by arrows in the figures) is called front face.

We will now detail these four different structures in more detail.

First of all, reference is made to the tandem structure 100 represented in Figure 2A. This NIP-type (or standard emitter) tandem structure 100 comprises:

- the first solar cell 110 with a silicon heterojunction (based on amorphous silicon and crystalline silicon) comprising from the rear face to the front face: a first layer made of N-doped amorphous silicon (for example a layer of n-doped hydrogenated amorphous silicon also denoted (n) a-Si:H) 111 and a substrate of doped crystalline silicon 112 (for example a substrate of n-doped crystalline silicon also denoted c-Si (n)) disposed between two layers of intrinsic amorphous silicon 113, 114 (also called layers of (i) a-Si:H or intrinsic hydrogenated amorphous silicon),

- a layer 121 based on P-type nanocrystalline or microcrystalline silicon (for example a layer of p+ doped hydrogenated microcrystalline silicon also denoted (p+) μ c-Si:H layer), which also serves as an emitter in the heterojunction cell,

- a second perovskite solar cell 130 comprising towards the front face: an N-type layer 133 (for example a layer made of SnO_2), an active layer 131 made of a perovskite material and a P-type layer 132 (for example a layer made of PTAA).

Reference is not made to the tandem structure 100 represented in Figure 2B. This PIN-type (or with an inverted emitter) tandem structure 100 comprises:

- the first solar cell 110 with a silicon heterojunction based on amorphous silicon and crystalline silicon comprising from the rear face to the front face: a P-type amorphous silicon layer 115 (for example a p-doped hydrogenated amorphous silicon layer, also denoted (p) a-Si:H), a substrate of doped crystalline silicon 112 (for example a c-Si(n) substrate) disposed between two layers of intrinsic amorphous silicon 113, 114 (for example (i) a-Si:H), and possibly a first layer of N-type amorphous silicon 111 (for example (n) a-Si:H), which is also the incubation layer of the nano or microcrystalline layer 122,

- a layer based on N-type nanocrystalline or microcrystalline silicon 122 (for example a layer of n+ doped hydrogenated microcrystalline silicon also denoted (n+) μ c-Si:H layer),

- a second perovskite solar cell 130 comprising towards the front face: a P-type layer 132 (for example a layer made of PTAA or TBF), an active layer 131 made of a perovskite material and an N-type layer 133 (for example a layer made of SnO_2 or a PCBM/ SnO_2 or PCBM/BCP bilayer).

In these two structures represented in Figures 2A and 2B, the layer based on nanocrystalline or microcrystalline silicon of the first conductivity type (P in the case of a NIP structure and N in the case of a PIN structure) is in direct contact with the layer of the second conductivity type (N in the case of a NIP structure and P in the case of a PIN structure) of the second cell 130. The recombination junction is located between the layer based on nanocrystalline or microcrystalline silicon of the first conductivity type and the charge carrier/extractor material of the second conductivity type of the second solar cell 130 (i.e. between the layers 121 and 133 for the NIP structure and between the layers 122 and 132 for the PIN structure).

Reference is now made to the tandem structure 100 represented in Figure 3A. This NIP-type (or standard emitter) tandem structure 100 comprises:

- a first solar cell 110 with a silicon heterojunction based on amorphous silicon and crystalline silicon comprising, from the rear face to the front face: a layer of N-type amorphous silicon 111 (for example (n) a-Si:H) and a substrate of crystalline silicon

112 (for example a c-Si (n) substrate) disposed between two layers of intrinsic amorphous silicon 113, 114 (for example (i) a-Si:H),

- a layer 121 based on P-type nanocrystalline or microcrystalline silicon which also serves as an emitter of the heterojunction cell (for example (p+) $\mu\text{c-Si:H}$) and a layer based on N-type nanocrystalline or microcrystalline silicon 122 (for example (n+) $\mu\text{c-Si:H}$),

- a second perovskite solar cell 130 comprising towards the front face: an active layer (131) made of a perovskite material and a P-type layer 132 (for example a layer made of PTAA).

Reference is not made to the tandem structure 100 represented in Figure 3B. This PIN-type (or with an inverted emitter) tandem structure 100 comprises:

- a first solar cell 110 with a silicon heterojunction based on amorphous silicon and crystalline silicon comprising from the rear face to the front face: a layer of P-type amorphous silicon 115 (for example (p) a-Si:H) and a substrate of crystalline silicon 112 (for example a c-Si (n) substrate) disposed between two layers of intrinsic amorphous silicon 113, 114 (for example (i) a-Si:H), possibly a layer of N-type amorphous silicon 111 (for example (n) a-Si:H), which is also the incubation layer of the nano or microcrystalline layer 121,

- a layer based on N-type nanocrystalline or microcrystalline silicon 121 (for example (n+) $\mu\text{c-Si:H}$) and a layer based on P-type nanocrystalline or microcrystalline silicon 122 (for example (p+) $\mu\text{c-Si:H}$),

- a second perovskite solar cell 130 comprising towards the front face: an active layer 131 made of a perovskite material and an N-type layer 133 (for example a layer made of SnO_2 or a PCBM/ SnO_2 bilayer).

In these two structures represented in Figures 3A and 3B, the layer based on P-type nanocrystalline or microcrystalline silicon 121 or 122 and the layer based on N-type nanocrystalline or microcrystalline silicon 122 or 121 form a tunnel junction 120. One of these layers is in direct contact with the active layer 131 of the second solar cell 130 and then also serves as a charge extractor in the second cell 130.

For these different tandem structures 100 disclosed before, the layers of P type (p+) and/or N type (n+) nanocrystalline or microcrystalline silicon may have a thickness ranging from 20 to 40 nm.

In the case of a P-doped layer, the Fermi level is between 4.5 and 5.9 eV.

In the case of an N-doped layer, the Fermi level is between 3.9 and 4.4 eV.

The nanocrystalline or microcrystalline silicon layers are heavily doped. The doping of the layers of (p+ or n+) nanocrystalline or microcrystalline silicon ranges, for example, from 10^{18} to 10^{22} /cm³.

Preferably, the layers based on nanocrystalline or microcrystalline silicon are made of $\mu\text{c-Si:H}$ (p+), $\mu\text{c-Si:H}$ (n+), N or P type nc-SiC_x or N or P type nc-SiO_y with x ranging from 0 to 1 and y from 0 to 2.

Advantageously, such layers have a high vertical conductivity, a low vertical resistance (typically lower than 0.5 Ohm.cm²) and/or a lateral conductivity higher than 10^{-3} S.cm⁻¹.

For example, the p/n type doping levels of the layers 111 and 115 are between 10^{18} and 10^{19} /cm³.

The silicon substrate 12 of the lower cell may be polished or textured (for example, it may consist of texturing in the form of 2 μm pyramids). The amorphous layers of the lower cell having a thickness of a few nanometres, they will take on the shape of the texturing of the substrate.

The N-type layer 133 of the perovskite cell 130 also called "electron transport layer" (or EIL standing for "Electron Injection Layer" or ETL standing for "Electron Transport Layer") is, for example, a metal oxide such as zinc oxide (ZnO), aluminium-doped zinc oxide also called AZO (ZnO:Al), titanium oxide (TiO₂) or tin oxide (SnO₂). It may also consist of a stack of methyl [6,6]-phenyl-C₆₁-butanoate and SnO₂ (PCBM/SnO₂) or methyl [6,6]-phenyl-C₆₁-butanoate and of bathocuproine (PCBM/BCP).

The P-type layer 132 of the perovskite cell 130 is also called "hole transport layer" (or HTL standing for "Hole Transport Layer"). For example, the P-type layer 132 is an organic compound like Poly(3,4- ethylenedioxythiophene) Polystyrene

sulfonate (PEDOT:PSS), [poly(bis 4-phenyl){2,4,6-trimethylphenyl} amine)] (PTAA), [Poly(*N,N'*-bis(4-butylphenyl)-*N,N'*-bis(phenyl)-benzidine) (Poly-TPD), 2,2',7,7'-Tetrakis[*N,N*-di(4-methoxyphenyl)amino]-9,9'-spirobifluorene (spiro-OMeTAD), *N*₄,*N*_{4'}-bis(4-(6-((3-ethyloxetan-3-yl)methoxy)hexyl)phenyl)-*N*₄,*N*_{4'}-diphenyl-[1,1'-biphenyl]-4,4'-diamine (OTPD), poly[(9,9-dioctylfluorenyl-2,7-diyl)-co-(4,4'-(*N*-(4-sec-butylphenyl)diphenylamine)] (TFB) or pyrene, or else a metal oxide such as a molybdenum oxide, a vanadium oxide or a tungsten oxide.

The active layer 131 of the perovskite cell 130 comprises at least one perovskite material. The perovskite material has the general formula ABX_3 with A representing one or more monovalent organic cation(s), such as an ammonium, like methylammonium or formamidinium, or a monovalent metal cation, like cesium or rubidium; B representing a divalent metal cation like Pb, Sn, Ag or a mixture thereof; and X representing one or more halide anion(s).

More particularly, the perovskite material may have the particular formula $H_2NCHNH_2PbX_3$ or $CH_3NH_3PbX_3$ with X a halogen. For example, it may consist of methylammonium lead iodide $CH_3NH_3PbI_3$. Preferably, the perovskite material has the formula $Cs_xFA_{1-x}Pb(I_{1-y}Br_y)_3$.

The tandem device 100 may also comprise:

- a first electrode 140 (lower electrode) disposed at the rear face; the lower electrode 140 may advantageously be opaque or of limited transparency, for example a transparent conductive oxide such as in particular ITO, IOH (hydrogenated indium oxide), or AZO

- a second electrode 150 (upper electrode) disposed over the front face of the device; the second electrode is electrically-conductive and optically-transparent, so as to let the photons pass up to the active layer 131 of the upper cell 130. This electrode 150 may be made of a transparent conductive oxide, typically indium-tin oxide (ITO) or aluminium-doped zinc oxide ($ZnO:Al$), IZO, IZrO, IWO, etc., or it may be formed of a transparent conductive polymer comprising silver nanowires for example,

- contact pads 160 at the rear face and contact pads 170 at the front face; the contact pads may for example be made of gold, aluminium or silver. (deposited for example by evaporation, or printed by screen-printing, inkjet printing, etc.).

Illustrative and non-limiting examples of one embodiment:

In this example, a conventional tandem structure and two simplified tandem structures have been selected.

The conventional tandem structure is represented in Figures 1A and 1B.

The simplified tandem structures 100 are represented in Figures 2A, 2B, 3A and 3B.

The following Tables 1 and 2 list the thicknesses of the simulated layers for NIP and PIN-type architectures respectively. The perovskite used in the simulations is of the $\text{Cs}_x\text{FA}_{1-x}\text{Pb}(\text{I}_{1-y}\text{Br}_y)_3$ type (with $x < 0.20$; $0 < y < 1$). Two different thicknesses have been used to obtain less current deviation between the two sub-cells when the surface condition is modified. The disclosed results will be with a perovskite that is 250 nm thick when the front face is polished and 415 nm thick when it is textured.

The following Table 1 lists the thicknesses (nm) of the simulated layers for the NIP-type architectures:

	Fig. 1A NIP	Fig.2A NIP	Fig.3A NIP
ITO front face	180	180	180
PTAA	30	30	30
Perovskite active layer	250 and 415	250 and 415	250 and 415
SnO₂	30	30	/
(n+) $\mu\text{c-Si:H}$	20	/	20
(p+) $\mu\text{c-Si:H}$	25	25	25
a-Si:H (p)	/	/	/
a-Si:H (i)	10	10	10
c-Si	280000	280000	280000
a-Si:H (i)	5	5	5
a-Si:H (n)	8	8	8
ITO rear face	70	70	70
Ag	200	200	200

The following Table 2 lists the thicknesses (nm) of the simulated layers for the PIN-type architectures:

	Fig.1B PIN	Fig. 2B PIN	Fig.3B PIN
ITO front face	180	180	180
SnO₂	30	30	30
Perovskite active layer	250 and 415	250 and 415	250 and 415
PTAA	30	30	/
(p+) μc-Si:H	16	/	16
(n+) μc-Si:H	24	24	24
a-Si:H (n)	8	8	8
a-Si:H (i)	5	5	5
c-Si	280000	280000	280000
a-Si:H (i)	5	5	5
a-Si:H (p)	19	19	19
ITO rear face	70	70	70
Ag	200	200	200

Optical simulations of these structures have been carried out using the CROWM software, while taking into account the optical indices of the layers, their thickness and the surface condition (completely flat, textured, etc.).

These simulations are performed between 310 and 1,200 nm with the AM1.5 solar spectrum. The optical indices have been extracted by ellipsometry from the experimental layers.

The obtained curves representing the external quantum efficiency (EQE) and the '1-R_{tot}' value are represented in Figures 4A, 4B, 5A, 5B, 6A and 6B.

This optical simulation study demonstrates that simplified NIP and PIN tandem structures with a junction made of microcrystalline silicon are viable regardless of texturing. Indeed, these simplified structures have only very few differences from an optical perspective with the complete structures and have the same optical potential.

Table 3 lists the values of J_{sc} and R_{tot} obtained by optical simulations, and the estimated PCEs for FF = 75% and V_{oc} = 1.8 V for conventional tandem structures (as represented in Figures 1A and 1B) and simplified tandem structures as represented in

Figures 2A, 2B and 3A, 3B. The front and rear faces of the tandem structures may be polished or textured independently of each other.

Front face	Rear face	NIP/PIN	Figure	J_{sc} PK (mA/cm ²)	J_{sc} Si (mA/cm ²)	PCE (%)	R_{tot} (mA/cm ²)
Conventional tandem structure							
polished	textured	NIP	1A	16.59	18.04	22.4	8.53
polished	textured	PIN	1B	16.82	17.4	22.71	9.61
polished	polished	NIP	1A	16.59	17	22.4	10.92
polished	polished	PIN	1B	16.82	16.47	22.23	11.85
textured	textured	NIP	1A	19.44	20.87	26.24	3.06
textured	textured	PIN	1B	19.94	20.64	26.92	3.33
Simplified tandem structure with a recombination junction located between the microcrystalline silicon layer and a charge transporter/extractor material of the perovskite sub-cell							
polished	textured	NIP	2A	16.7	17.7	22.55	8.97
polished	textured	PIN	2B	16.84	17.42	22.73	9.62
polished	polished	NIP	2A	16.7	16.75	22.55	11.21
polished	polished	PIN	2B	16.84	16.47	22.23	11.87
textured	textured	NIP	2A	19.55	20.77	26.39	3.16
textured	textured	PIN	2B	19.91	20.7	26.88	3.33
Simplified tandem structure with a recombination junction comprising two microcrystalline silicon layers, one of the microcrystalline silicon layers serving as a charge extractor of the perovskite sub-cell							
polished	textured	NIP	3A	16.39	18.09	22.13	8.53
polished	textured	PIN	3B	16.59	17.63	22.4	9.47
polished	polished	NIP	3A	16.39	16.98	22.13	11.1
polished	polished	PIN	3B	16.59	16.6	22.4	11.91
textured	textured	NIP	3A	19.25	21.14	25.99	2.97
textured	textured	PIN	3B	19.74	20.91	26.65	3.24

- 5 The simplified tandem structures represented in Figures 3A and 3B prove to be different from the others in terms of distribution of the absorption in the tandem cell, however the resulting short-circuit currents are very similar.

CLAIMS

1. A 2-terminal tandem photovoltaic structure (100) comprising from the rear face to the front face:

5 - a first solar cell (110) with a silicon heterojunction comprising, from the rear face to the front face: a first layer of a first conductivity type made of amorphous silicon and a substrate of crystalline silicon (112) of the first conductivity type or of a second conductivity type, disposed between two layers of intrinsic amorphous silicon (113, 114), and possibly a first layer of a second conductivity type made of amorphous
10 silicon,

 - a recombination zone comprising a layer based on nanocrystalline or microcrystalline silicon of the second conductivity type, and a second layer of the first conductivity type, possibly based on nanocrystalline or microcrystalline silicon of the first conductivity type,

15 - an active layer (131) made of a perovskite material and a second layer of a second conductivity type,

 characterised in that the second layer of the first conductivity type of the recombination zone is in contact with the active layer made of a perovskite material (131) and with the layer based on nanocrystalline or microcrystalline silicon of the second
20 conductivity type of the recombination zone.

2. The tandem structure (100) according to claim 1, characterised in that the layer based on nanocrystalline or microcrystalline silicon of the first conductivity type and/or the layer based on nanocrystalline or microcrystalline silicon of the second
25 conductivity type is made of $\mu\text{c-Si}:\text{H}(\text{p}+)$, $\mu\text{c-Si}:\text{H}(\text{n}+)$, N or P type nc-SiC_x or N or P type nc-SiO_y with x ranging from 0 to 1 and y ranging from 0 to 2.

3. The tandem structure (100) according to any one of the preceding claims, characterised in that the layer based on nanocrystalline or microcrystalline silicon
30 of the first conductivity type and/or the layer based on silicon nanocrystalline or

microcrystalline of the second conductivity type has a thickness ranging from 15 nm to 60 nm and preferably from 20 to 40 nm.

4. The tandem structure (100) according to any one of the preceding claims, characterised in that the layer based on nanocrystalline or microcrystalline silicon of the first conductivity type and/or the layer based on nanocrystalline or microcrystalline silicon of the second conductivity type has a conductivity higher than $10^{-3} \text{ S.cm}^{-1}$.

5. The tandem structure (100) according to any one of the preceding claims, characterised in that the layer based on nanocrystalline or microcrystalline silicon of the first conductivity type and/or the layer based on nanocrystalline or microcrystalline silicon of the second conductivity type has a doping level of $10^{18}/\text{cm}^3$ to $10^{22}/\text{cm}^3$.

6. The tandem structure (100) according to one of claims 1 to 5, characterised in that the first conductivity type is of the N type.

7. The tandem structure (100) according to claim 6, characterised in that it comprises from the rear face to the front face:

- the first solar cell (110) with a silicon heterojunction based on amorphous silicon and crystalline silicon comprising, from the rear face to the front face: the first N-type layer (111) made of amorphous silicon and the substrate of crystalline silicon (112) disposed between the two layers of intrinsic amorphous silicon (113, 114),

- the layer (121) based on P-type nanocrystalline or microcrystalline silicon,

- a second perovskite solar cell (130) comprising towards the front face: the second N-type layer (133), preferably made of SnO_2 , the active layer (131) made of a perovskite material and the second P-type layer (132) preferably made of PTAA.

8. The tandem structure (100) according to claim 6, characterised in that it comprises from the rear face to the front face:

- the first solar cell (110) with a silicon heterojunction based on amorphous silicon and crystalline silicon comprising, from the rear face to the front face: the first N-type layer (111) made of amorphous silicon and the substrate of crystalline silicon (112) disposed between the two layers of intrinsic amorphous silicon (113, 114),

5 - the layer (121) based on P-type nanocrystalline or microcrystalline silicon and the layer (122) based on N-type nanocrystalline or microcrystalline silicon,

- the second perovskite solar cell (130) comprising towards the front face: the active layer (131) made of a perovskite material and the second P-type layer (132) preferably made of PTAA.

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9. The tandem structure (100) according to one of claims 1 to 5, characterised in that the first conductivity type is of the P type.

15 10. The tandem structure (100) according to claim 9, characterised in that it comprises from the rear face to the front face:

- the first solar cell (110) with a silicon heterojunction based on amorphous silicon and crystalline silicon comprising, from the rear face to the front face: the first P-type layer (115) made of amorphous silicon, the substrate of crystalline silicon (112) disposed between the two layers of intrinsic amorphous silicon (113, 114), and the
20 first N-type layer (111) made of amorphous silicon,

- the layer (122) based on N-type nanocrystalline or microcrystalline silicon,

- a second perovskite solar cell (120) comprising towards the front face: the second P-type layer (132), preferably made of PTAA or TFB, the active layer (131)
25 made of a perovskite material and the second N-type layer (133) preferably made of SnO₂ or a PCBM/SnO₂ bilayer.

11. The tandem structure (100) according to claim 9, characterised in that it comprises from the rear face to the front face:

- the first solar cell (110) with a silicon heterojunction based on amorphous silicon and crystalline silicon comprising, from the rear face to the front face: the first P-type layer (115) made of amorphous silicon, the substrate of crystalline silicon (112) disposed between the two layers of intrinsic amorphous silicon (113, 114), and the first N-type layer (111) made of amorphous silicon,

- the layer (121) based on N-type nanocrystalline or microcrystalline silicon and the layer (122) based on P-type nanocrystalline or microcrystalline silicon,

- a second perovskite solar cell (130) comprising towards the front face: the active layer (131) made of a perovskite material and the second N-type layer (133) preferably made of SnO_2 or a PCBM/ SnO_2 bilayer.