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Lin et al.

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(54) HOT-CARRIER PHOTOELECTRIC CONVERSION METHOD

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H01L 51/00	(2006.01)

(52) **U.S. Cl.**

CPC ***H01L 31/06*** (2013.01); ***H01L 51/4213*** (2013.01); *H01L 51/0039* (2013.01); *Y02E 10/549* (2013.01)

(58) **Field of Classification Search**

CPC H01L 51/42; H01L 31/06; H01L 51/4213

See application file for complete search history.

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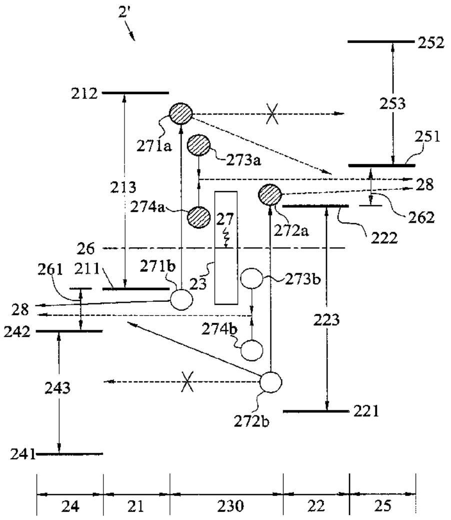
(57) ABSTRACT

The present invention provides a hot-carrier photoelectric conversion method. The method includes a hot-carrier photoelectric conversion device having a P-type semiconductor layer, an N-type semiconductor layer, and an inorganic conducting light-absorbing layer. The inorganic conducting light-absorbing layer is formed between the P-type semiconductor layer and the N-type semiconductor layer, and an electric field is formed between the P-type semiconductor layer and the N-type semiconductor layer. Moreover, photons are absorbed by the inorganic conducting light-absorbing layer to create electrons and holes. The electrons and holes are respectively shifted by the electric field or diffusion effect to the N-type semiconductor layer and the P-type semiconductor layer, so that the electrons and the holes are respectively conducted outside to create electric energy. Further, the present invention increases the quantity of photons absorbed, and makes electrons and holes be quickly conducted outside, thereby increasing photoelectric conversion efficiency, and creating electric energy with a high open-circuit voltage and a high current.

13 Claims, 8 Drawing Sheets



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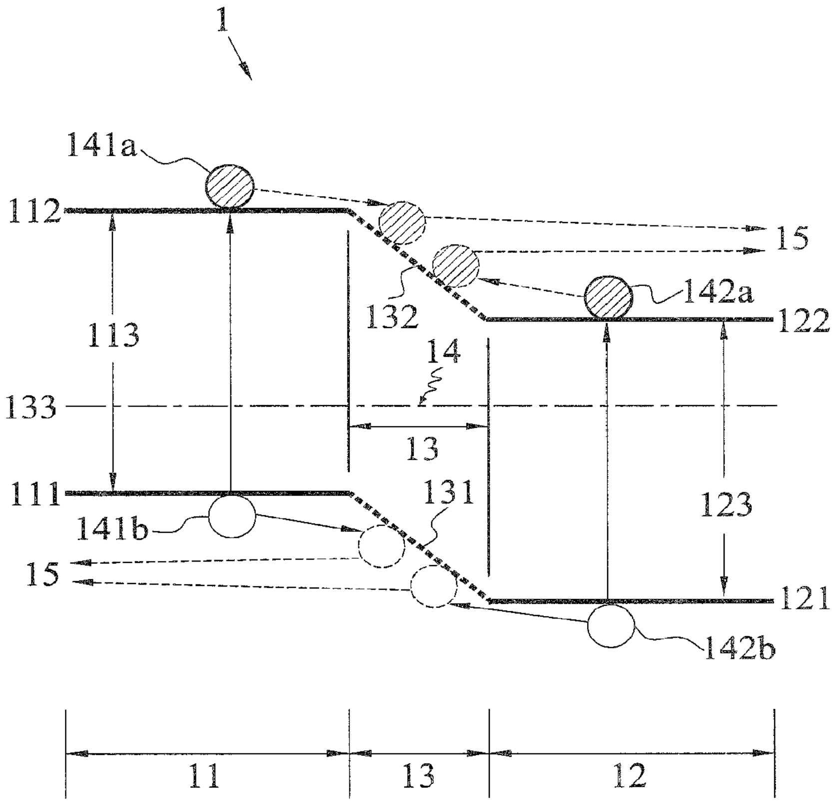


FIG. 1 (PRIOR ART)

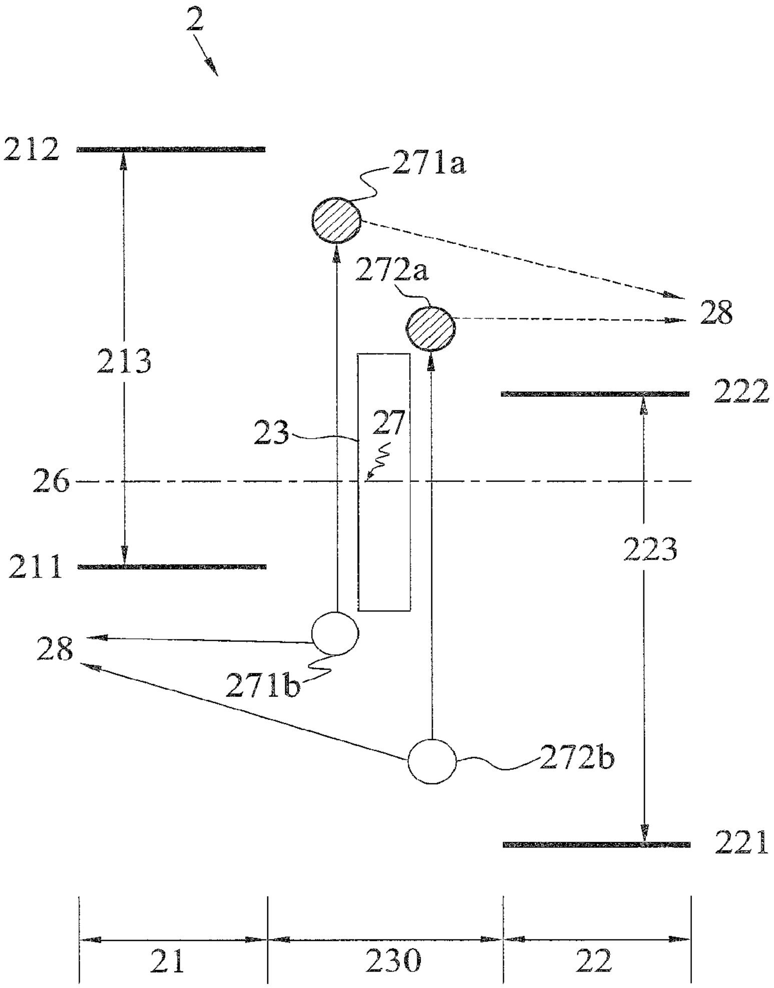
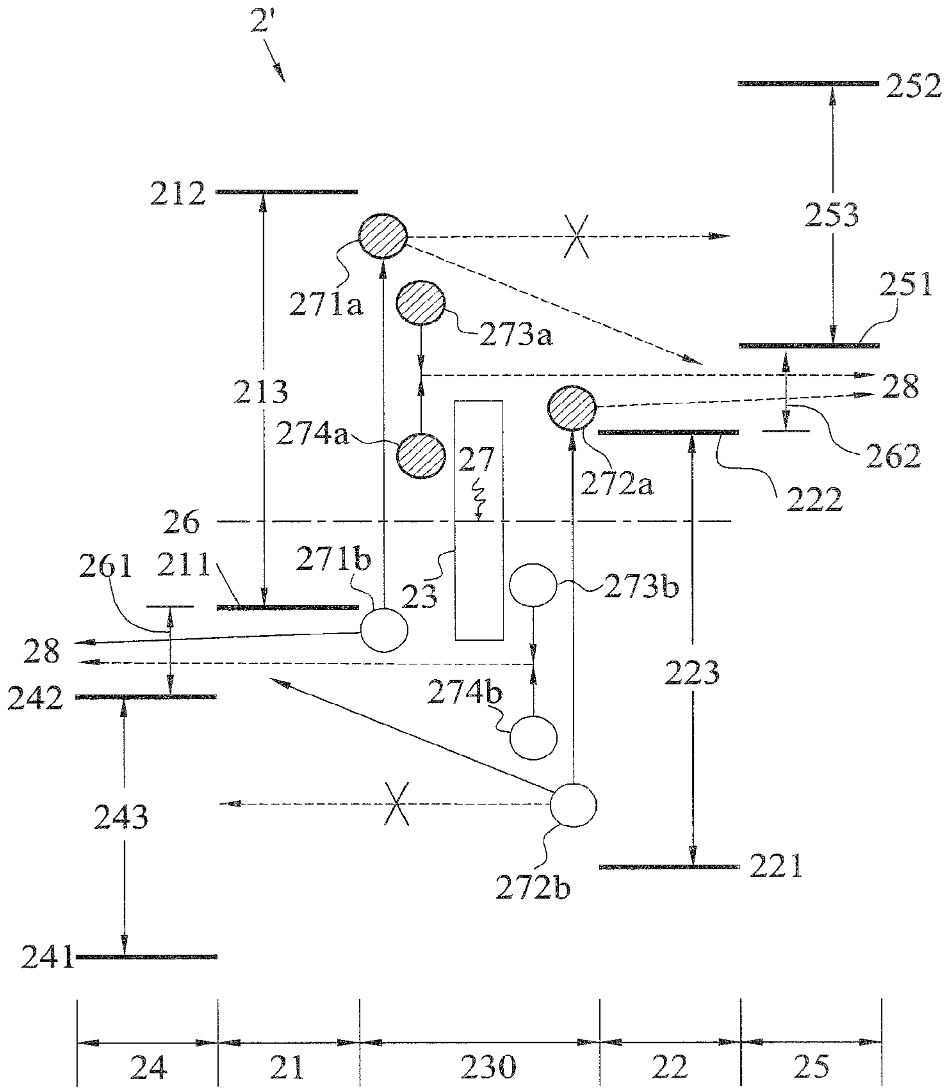

2
212
271a
272a
28
213
222
23
27
26
223
211
28
271b
272b
221
21
230
22

FIG. 2


2'
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212
253
251
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273a
28
213
274a
27
272a
262
222
26
261
211
271b
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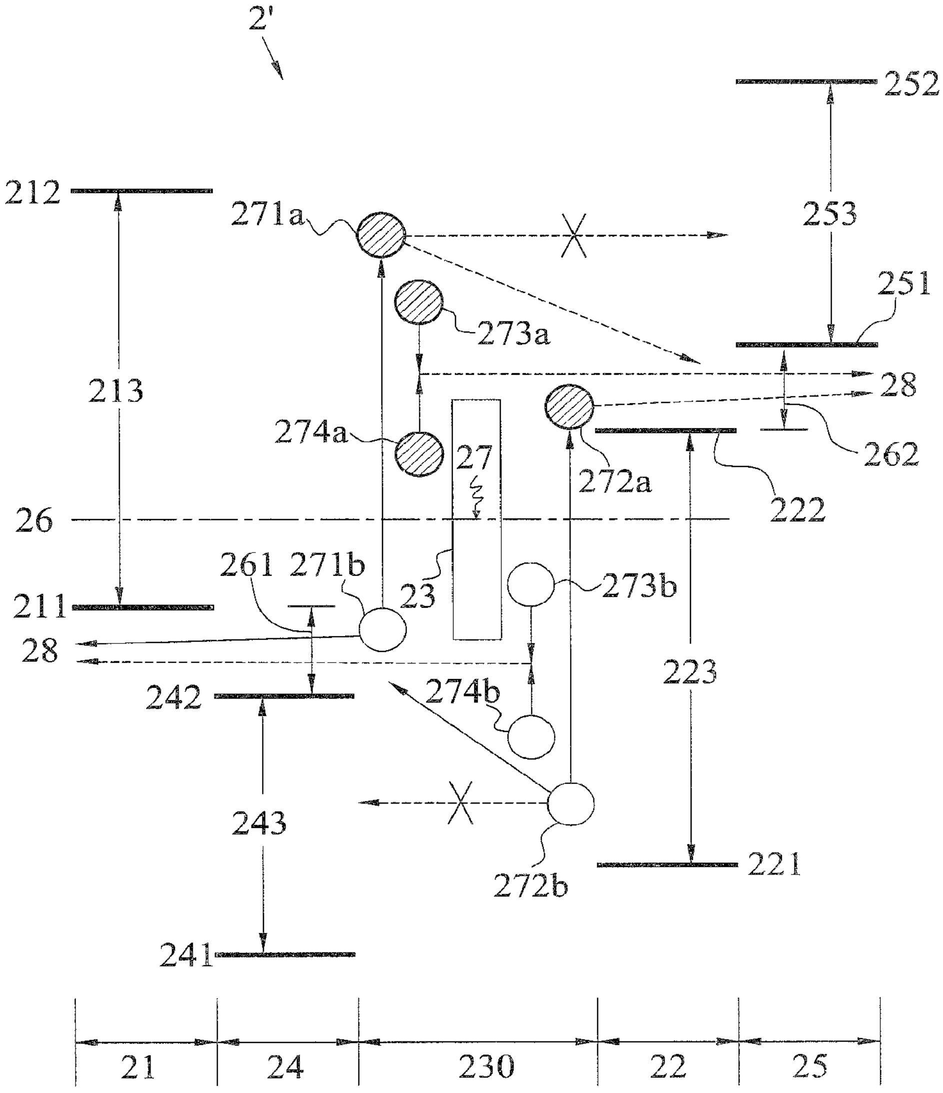
273b
28
242
223
274b
243
272b
221
241
24
21
230
22
25

FIG. 3A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271a
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273a
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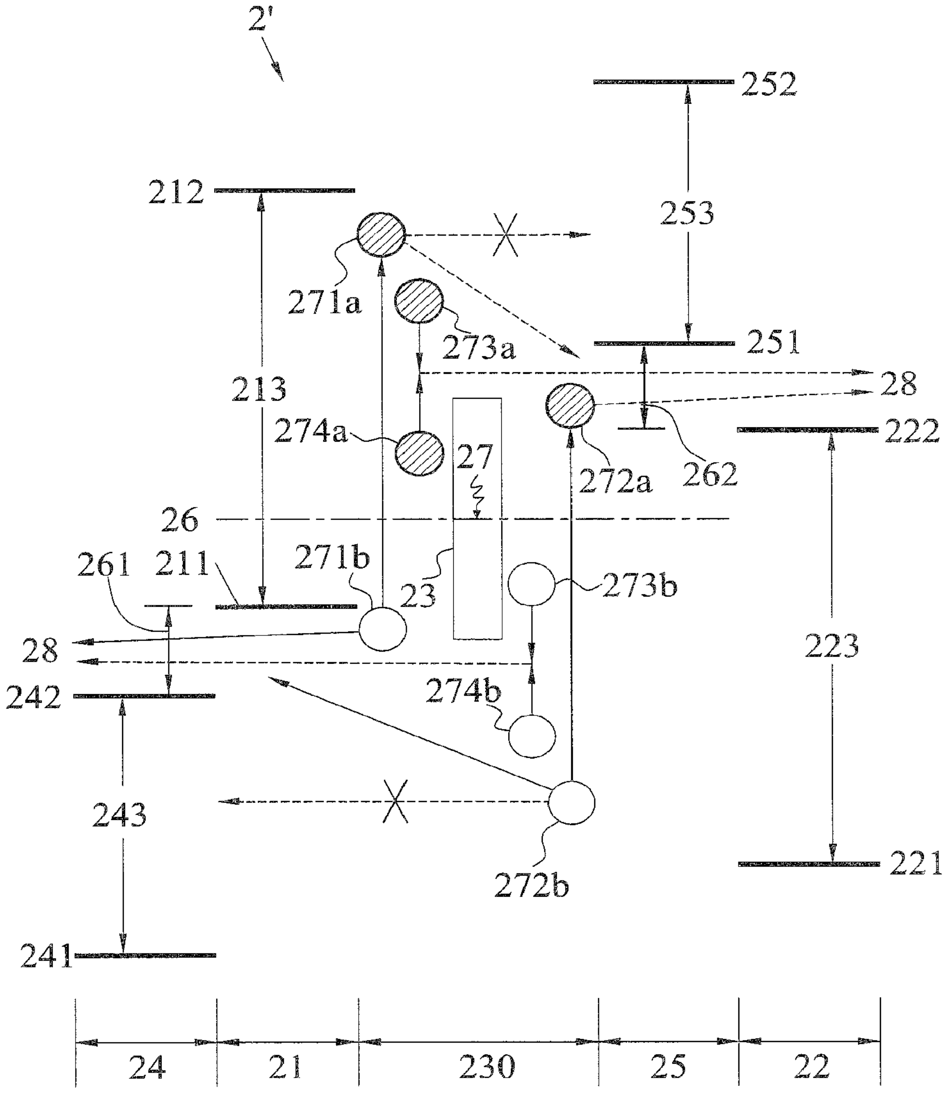
274a
27
262
272a
222
26
261
271b
273b
23
211
28
223
242
274b
243
221
272b
241
21
24
230
22
25

FIG. 3B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261
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271b
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273b
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242
274b
223
243
272b
221
241
24
21
230
25
22

FIG. 3C

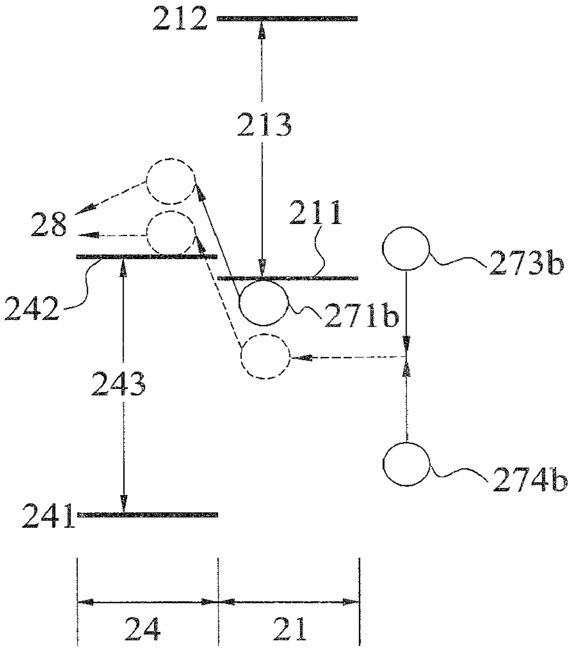

FIG. 4A

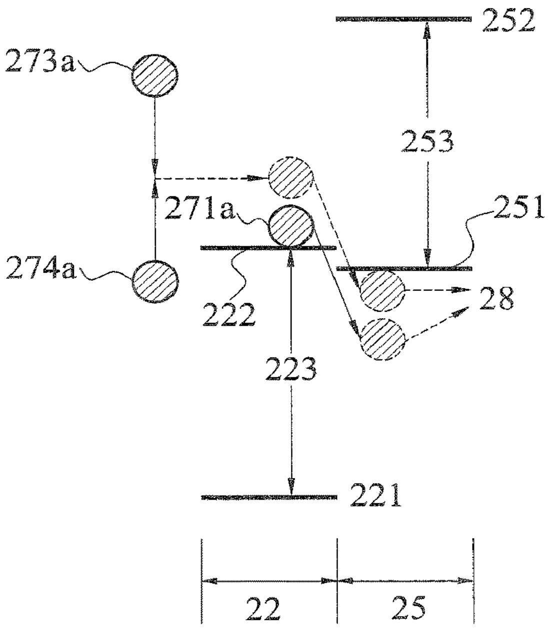

FIG. 4B

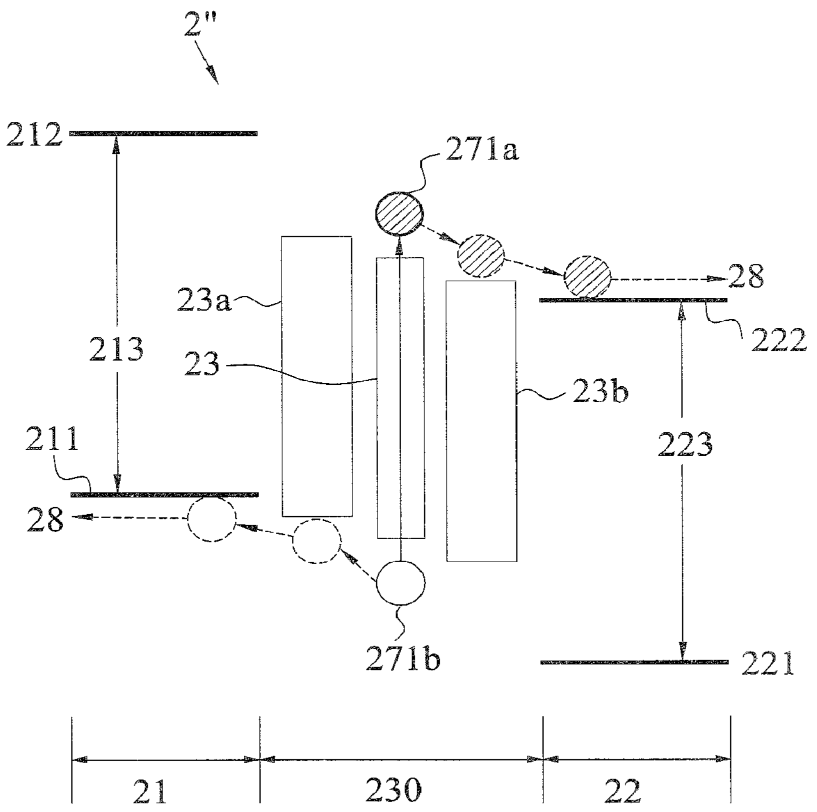

FIG. 5

HOT-CARRIER PHOTOELECTRIC CONVERSION METHOD

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a divisional of copending application U.S. Ser. No. 14/183,927, filed on Feb. 19, 2014, which claims under 35 U.S.C § 119(a) the benefit of Taiwanese Application No. 102119892, filed Jun. 5, 2013, the entire contents of which are incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates to a photoelectric conversion device and a method thereof, and more particularly, to a hot-carrier photoelectric conversion device and a method thereof.

BACKGROUND OF THE INVENTION

FIG. **1** shows a schematic diagram of a traditional photoelectric conversion device **1** and a photoelectric conversion method thereof. As shown in FIG. **1**, the photoelectric conversion device **1** includes a P-type semiconductor layer **11** and an N-type semiconductor layer **12**.

The P-type semiconductor layer **11** has a first valence band **111**, a first conduction band **112**, and a first bandgap **113**. The N-type semiconductor layer **12** has a second valence band **121**, a second conduction band **122**, and a second bandgap **123**. A depletion zone **13** is formed on the PN junction between the P-type semiconductor layer **11** and the N-type semiconductor layer **12**. An internal electric field is created in the depletion zone **13**.

A first potential slope **131** is formed between the first valence band **111** and the second valence band **121**, and all three are below the Fermi level **133**. A second potential slope **132** is formed between the first conduction band **112** and the second conduction band **122**, and all three are above the Fermi level **133**.

When the photoelectric conversion device **1** absorbs a plurality of photons **14** and produces electron-hole pairs such as a first electron **141***a* and a first hole **141***b*, and a second electron **142***a* and a second hole **142***b*, the first electron **141***a* may transition from the first valence band **111** to the first conduction band **112**, and the second electron **142***a* may transition from the second valence band **121** to the second conduction band **122**.

Then, owing to the diffusion effect, the first electron **141***a* and the second electron **142***a* may arrive on the second potential slope **132** of the depletion zone **13**, and the first hole **141***b* and the second hole **142***b* may arrive below the first potential slope **131** of the depletion zone **13**. Next, with the internal electric field in the depletion zone **13**, the first electron **141***a*, the second electron **142***a*, the first hole **141***b* and the second hole **142***b* are separately transferred to an external circuit **15**, thereby creating electrical energy.

One disadvantage of such conventional photoelectric conversion device is that both the P-type semiconductor layer and the N-type semiconductor layer have bandgaps. For example, the band gap of a P-type semiconductor layer or an N-type semiconductor layer made of silicon (Si) is about 1.1 eV (electron volts). As a result, the light absorption range of the photoelectric conversion device is restricted by the bandgaps, such that some photons cannot be absorbed by the photoelectric conversion device, resulting in a reduction in the number of photons being absorbed, and failure in producing a large amount of electrons and holes.

Furthermore, the electrons and holes are conducted externally at a lower rate with a lower capture, resulting in high energy loss, smaller voltage and current, and poorer photoelectric conversion efficiency. As a result, the photoelectric conversion device can only obtain a small number of low-energy electrons and holes (cold carrier), and produces electricity of a low voltage and a low current.

Therefore, there is a need to develop a photoelectric conversion device and a method thereof to overcome the above problems.

SUMMARY OF THE INVENTION

The present invention provides a hot-carrier photoelectric conversion device, which includes a P-type semiconductor layer; an N-type semiconductor layer; and an inorganic conducting light-absorbing layer formed between the P-type semiconductor layer and the N-type semiconductor layer.

The P-type semiconductor layer or the N-type semiconductor layer is a transparent or partially transparent semiconductor, so that photons pass through the transparent or partially transparent semiconductor layer to the inorganic conducting light-absorbing layer so as to create electrons and holes. Both the P-type semiconductor layer and the N-type semiconductor layer are inorganic semiconductor layers or organic semiconductor layer, or one is an inorganic semiconductor layer and the other one is an organic semiconductor layer.

The present invention further provides a hot-carrier photoelectric conversion method, which includes: providing a hot-carrier photoelectric conversion device including a P-type semiconductor layer, an N-type semiconductor layer, and an inorganic conducting light-absorbing layer, wherein the inorganic conducting light-absorbing layer is provided between the P-type semiconductor layer and the N-type semiconductor layer, and an electric field is formed between the P-type semiconductor layer and the N-type semiconductor layer.; absorbing photons with the inorganic conducting light-absorbing layer to create electrons and holes; and shifting the electrons and holes to the N-type semiconductor layer and the P-type semiconductor layer by an electric field or diffusion effect, respectively, so that the electrons and the holes are respectively conducted outside to create electric energy.

From the above, it can be understood that the hot-carrier photoelectric conversion device and the photoelectric conversion method of the present invention includes forming the inorganic conducting light-absorbing layer between the P-type semiconductor layer and the N-type semiconductor layer for absorbing photons, and the electrons and holes are respectively conducted outside to create electric energy. Therefore, the present invention may absorb photons of any wavelengths, increase the quantity of photons absorbed, and make large amounts of high-energy electrons and holes (hot carriers) be quickly conducted outside, thereby increasing the photoelectric conversion efficiency, and creating electric energy with a high open-circuit voltage and a high current.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention can be more fully understood by reading the following detailed description of the preferred embodiments, with reference made to the accompanying drawings, wherein:

FIG. **1** is a schematic diagram illustrating the basic structure of a traditional photoelectric conversion device and photoelectric conversion method thereof;

FIG. **2** is a schematic diagram illustrating the basic structure of a hot-carrier photoelectric conversion device and a photoelectric conversion method thereof according to a first embodiment of the present invention;

FIG. **3**A is a schematic diagram illustrating the basic structure of a hot-carrier photoelectric conversion device and a photoelectric conversion method thereof according to a second embodiment of the present invention;

FIGS. **3**B to **3**C are schematic diagrams illustrating alternatives of the basic structure of a hot-carrier photoelectric conversion device and a photoelectric conversion method thereof according to the second embodiment of the present invention;

FIG. **4**A is a schematic diagram illustrating the P-type semiconductor layer and the first semiconductor layer according to the present invention;

FIG. **4**B is a schematic diagram illustrating the N-type semiconductor layer and the second semiconductor layer according to the present invention; and

FIG. **5** is a schematic diagram illustrating the basic structure of a hot-carrier photoelectric conversion device and a photoelectric conversion method thereof according to a third embodiment of the present invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

The present invention is described by the following specific embodiments. Those with ordinary skills in the arts can readily understand the other advantages and functions of the present invention after reading the disclosure of this specification.

It should be noted that the structures, proportions, sizes and the like shown in the attached drawings are to be considered only in conjunction with the contents of this specification to facilitate understanding and reading of those skilled in the art, and are not intended to limit the scope of present invention, thus they do not hold any real technically significance, and any changes or modifications in the structures, the proportions, the sizes and the like should fall within the scope of the technical contents disclosed in the present invention as long as they do not affect the effects and the objectives achieved by the present invention.

Meanwhile, terms such as “first”, “second” and the like recited in this specification are for illustration purposes only, and are not intended to limit the scope of the present invention in any way, any changes or modifications of the relative relationships of elements are therefore to be construed as with the scope of the present invention as long as there is no substantial changes to the technical contents.

FIG. **2** illustrates the basic structure of a hot-carrier photoelectric conversion device **2** and a photoelectric conversion method thereof according to a first embodiment of the present invention. As shown in FIG. **2**, the hot-carrier photoelectric conversion device **2** is a photoelectric conversion element and includes a P-type semiconductor layer **21**, an N-type semiconductor layer **22** and an inorganic conducting light-absorbing layer **23**. Both the P-type semiconductor layer **21** and the N-type semiconductor layer **22** can be inorganic semiconductor layers or organic semiconductor layers, or one is an inorganic semiconductor layer and the other is an organic semiconductor layer.

The P-type semiconductor layer **21** has a first valence band **211**, a first conduction band **212**, and a first bandgap **213** formed between the first valence band **211** and the first conduction band **212**. The first valence band **211** and the first conduction band **212** are below and above the Fermi level **26**, respectively. A P-type semiconductor layer with a higher-energy first conduction band **212** can be chosen to prevent recombination caused by electrons diffusing into the P-type semiconductor layer, which may reduce the carriers collected.

The N-type semiconductor layer **22** has a second valence band **221**, a second conduction band **222**, and a second band gap **223** formed between the second valence band **221** and the second conduction band **222**. The second valence band **221** and the second conduction band **222** are below and above the Fermi level **26**, respectively. An N-type semiconductor layer with a lower-energy second valence band **221** can be chosen to prevent recombination caused by holes diffusing into the N-type semiconductor layer, which may reduce the carriers collected.

The inorganic conducting light-absorbing layer **23** is provided between the P-type semiconductor layer **21** and the N-type semiconductor layer **22** for absorbing a plurality of photons in order to create electron-hole pairs such as a first electron **271***a* and a first hole **271***b*, and a second electron **272***a* and a second hole **272***b*. With an electric field or diffusing effect, the first electron **271***a*, the second electron **272***a* and the like move to be above the second conduction band **222** of the N-type semiconductor layer **22**, while the first hole **271***b*, the second hole **272***b*, and the like move to be below the first valence band **211** of the P-type semiconductor layer **21**. Thus, the first electron **271***a* and the second electron **272***a*, the first hole **271***b* and the second hole **272***b*, and the like are separately transferred to an external circuit **28**, thereby obtaining a large amount of hot carriers with high energy such as the first electron **271***a*, the second electron **272***a*, the first hole **271***b* and the second hole **272***b*, and producing electrical energy having a high open-circuit voltage and a high current.

The inorganic conducting light-absorbing layer **23** can be made of a material such as a metal, graphite, graphene, and so on. Its thickness can be less than 50 nm (1 nm=10^{-9} m), or less than or equal to a length five times the mean free path of the first electron **271***a*, first hole **271***b* or the like within the inorganic conducting light-absorbing layer **23**. When the thickness of the inorganic conducting light-absorbing layer **23** is less than the mean free path, it means that the first electron **271***a*, the first hole **271***b*, and the like are conducted outside before collision with the atoms (before energy is dissipated), so that the first electron **271***a*, the first hole **271***b*, and the like conducted outside have high energy.

Moreover, if absorbing more photons **27** is desired, the P-type semiconductor layer **21** or the N-type semiconductor layer **22** can be made into a nanostructure, and the inorganic conducting light-absorbing layer **23** is formed on the surface of this nanostructure in such a way that it conforms with the nanostructure. This increases the equivalent light-absorbing thickness, and thus increases the light absorption of the hot-carrier photoelectric conversion device **2**. Meanwhile, the inorganic conducting light-absorbing layer **23** is very closely located to the neighboring P-type semiconductor layer **21** or N-type semiconductor layer **22**, so the traveling distance for the first hole **271***b*, the first electron **271***a*, or the like to the P-type semiconductor layer **21** or the N-type semiconductor layer **22** is less than or close to the mean free path.

As the thickness of the inorganic conducting light-absorbing layer **23** is close to the mean free path of the first electron **271***a*, the first hole **271***b*, and the like, when the first electron

271*a* and the first hole **271***b* are moved to the P-type semiconductor layer **21** and the N-type semiconductor layer **22**, respectively, they do not go through several times of phonon scattering, and thus reserve higher energy, and the first electron **271***a*, the first hole **271***b*, and the like become the so-called hot carriers.

On the other hand, if the first electron **271***a* and the first hole **271***b* have lower energy, some of the energy can be transferred from higher-energy hot carriers to lower-energy hot carriers through carrier collisions. As a result, the inorganic conducting light-absorbing layer **23** may not necessarily have a bandgap, in other words, it can absorb the whole spectrum of the sunlight or various kinds of light.

FIG. **3**A is a schematic diagram illustrating the basic structure of a hot-carrier photoelectric conversion device **2'** and the photoelectric conversion method thereof according to a second embodiment of the present invention. The hot-carrier photoelectric conversion device **2'** and the photoelectric conversion method are similar to the hot-carrier photoelectric conversion device **2** and photoelectric conversion method, as described in FIG. **2**, and the major differences between them are as follows.

As shown in FIG. **3**A, the hot-carrier photoelectric conversion device **2'** further includes a first semiconductor layer **24** and a second semiconductor layer **25** made of N-type or P-type semiconductor.

The first semiconductor layer **24** is formed on the P-type semiconductor layer **21**, and includes a third valence band **241**, a third conduction band **242**, and a third bandgap **243** formed between the third valence band **241** and the third conduction band **242**. The energy level of the third conduction band **242** of the first semiconductor layer **24** is lower than the first valence band **211** of the P-type semiconductor layer **21**, such that a first energy-level channel **261** is formed between the third conduction band **242** and the first valence band **211**. The first hole **271***b* to a fourth hole **274***b* and the like may be conducted to the external circuit **28** through the first energy-level channel **261**, thereby obtaining a large amount of high-energy hot carriers (the first hole **271***b* to the fourth hole **274***b* and the like). A P-type semiconductor layer with a higher-energy first conduction band **212** can be chosen to prevent electrons from diffusing into the P-type semiconductor layer, which may reduce the carriers collected.

Moreover, when the energy of the fourth hole **274***b* is greater than the energy level of the first energy-level channel **261**, the fourth hole **274***b* cannot pass through the first semiconductor layer **24** or the third band gap **243**. In this case, the energy can be redistributed between a lower-energy third hole **273***b* and the higher-energy fourth hole **274***b*, so that the fourth hole **274***b* may be conducted to the external circuit **28** through the first energy-level channel **261**. As such, the number of holes that are conducted to the external circuit **28** can be increased.

Similarly, when the energy of the second hole **272***b* is greater than the energy level of the first energy-level channel **261**, the second hole **272***b* cannot pass through the first semiconductor layer **24** or the third bandgap **243**. In this case, the energy can be redistributed between a lower-energy hole and the higher-energy second hole **272***b*, so that the second hole **272***b* may be conducted to the external circuit **28** through the first energy-level channel **261**, thereby increasing the number of holes that can be conducted to the external circuit **28**.

Furthermore, the second semiconductor layer **25** is formed on the N-type semiconductor layer **22**, and includes a fourth valence band **251**, a fourth conduction band **252**, and a fourth bandgap **253** formed between the fourth valence band **251** and the fourth conduction band **252**. The energy level of the fourth valence band **251** of the second semiconductor layer **25** is higher than the second conduction band **222** of the N-type semiconductor layer **22**, such that a second energy-level channel **262** is formed between the fourth valence band **251** and the second conduction band **222**. The first electron **271***a* to a fourth electron **274***a* and the like may be conducted to the external circuit **28** through the second energy-level channel **262**, thereby obtaining a large amount of high-energy hot carriers (the first electron **271***a* to the fourth electron **274***a* and the like). An N-type semiconductor layer with a lower-energy second valence band **221** can be chosen to prevent holes from diffusing into the N-type semiconductor layer, which may reduce the carriers collected.

Moreover, when the energy of a third electron **273***a* is greater than the energy level of the second energy-level channel **262**, the third electron **273***a* cannot pass through the second semiconductor layer **25** or the fourth band gap **253**. In this case, the energy can be redistributed between the lower-energy fourth electron **274***a* and the higher-energy third electron **273***a*, so that the third electron **273***a* may be conducted to the external circuit **28** through the second energy-level channel **262**, thereby increasing the number of electrons that can be conducted to the external circuit **28**.

Similarly, when the energy of the first electron **271***a* is greater than the energy level of the second energy-level channel **262**, the first electron **271***a* cannot pass through the second semiconductor layer **25** or the fourth band gap **253**. In this case, the energy can be redistributed between a lower-energy electron and the higher-energy first electron **271***a*, so that the first electron **271***a* may be conducted to the external circuit **28** through the second energy-level channel **262**, thereby increasing the number of electrons that can be conducted to the external circuit **28**.

In the second embodiment, the redistribution of energy can be applied to both the electrons and the holes at the same time, or to just the electrons or the holes. As electrons are generally spread across a wider energy range, energy redistribution is usually applied to electrons in actual practice, thus allowing the hot-carrier photoelectric conversion device **2'** to create more hot carriers (electrons).

FIGS. **3**B to **3**C are schematic diagrams illustrating alternatives of the basic structure of a hot-carrier photoelectric conversion device **2'** and the photoelectric conversion method thereof according to the second embodiment of the present invention. The hot-carrier photoelectric conversion devices **2'** of FIGS. **3**B and **3**C are similar to that described in FIG. **3**A with some differences as follows.

As shown in FIG. **3**A, the first semiconductor layer **24** is formed on the P-type semiconductor layer **21**, whereas as shown in FIG. **3**B, the first semiconductor layer **24** is formed between the P-type semiconductor layer **21** and the inorganic conducting light-absorbing layer **23**.

Similarly, as shown in FIG. **3**A, the second semiconductor layer **25** is formed on the N-type semiconductor layer **22**, whereas as illustrated in FIG. **3**C, the second semiconductor layer **25** is formed between the N-type semiconductor layer **22** and the inorganic conducting light-absorbing layer **23**.

That is, the order of the first semiconductor layer **24** and the P-type semiconductor layer **21** may be reversed. Also, the order of the second semiconductor layer **25** and the N-type semiconductor layer **22** may be reversed. Three embodiments with respect to the above orders are illustrated in FIGS. **3**A, **3**B, and **3**C. According to the present invention, more than 3 combinations can be derived from the above disclosures.

FIG. **4**A illustrates an alternative of the P-type semiconductor layer **21** and the first semiconductor layer **24** of the present invention, which may be used instead of the P-type semiconductor layer **21** and the first semiconductor layer **24**, as shown in FIG. **3**. The P-type semiconductor layers **21** and first semiconductor layers **24**, as shown in FIGS. **4**A and FIG. **3**, are similar but have some differences as follows.

As shown in FIG. **4**A, for the P-type semiconductor layer **21** and the first semiconductor layer **24**, when the third conduction band **242** of the first semiconductor layer **24** is higher than the first valence band **211** of the P-type semiconductor layer **21**, the first hole **271***b* on the first valence band **211** of the P-type semiconductor layer **21** theoretically cannot directly pass through the first semiconductor layer **24**. However, when the difference in energy between the third conduction band **242** of the first semiconductor layer **24** and the first valence band **211** of the P-type semiconductor layer **21** is less than 0.1~0.2 eV, the first hole **271***b* may jump onto the third conduction band **242** of the first semiconductor layer **24** by phonon collision, where it is conducted to the external circuit **28** through the third conduction band **242** or an energy-level channel.

In addition, as for the lower-energy third hole **273***b* and the higher-energy fourth hole **274***b* that are not on the first valence band **211** of the P-type semiconductor layer **21**, they can also be moved onto the first valence band **211** of the P-type semiconductor layer **21** by energy redistribution, and jump onto the third conduction band **242** of the first semiconductor layer **24** through phonon collision, thereby allowing both the third hole **273***b* and the fourth hole **274***b* to be conducted to the external circuit **28** via the third conduction band **242** or the first energy-level channel **261**.

From FIGS. **3**A and **4**A, it can be seen that the hot-carrier photoelectric conversion device **2'** of the present invention may choose the appropriate P-type semiconductor layer **21** and the first semiconductor layer **24** for collecting holes (hot carriers).

FIG. **4**B is a schematic diagram illustrating an alternative of the N-type semiconductor layer **22** and second semiconductor layer **25** of the present invention, which can be used to replace the N-type semiconductor layer **22** and the second semiconductor layer **25**, as shown in FIG. **3**. The N-type semiconductor layer **22** and second semiconductor layer **25**, as shown in FIG. **4**B and FIG. **3**, are similar but have some differences as follows.

As shown in FIG. **4**B, for the N-type semiconductor layer **22** and second semiconductor layer **25**, when the fourth valence band **251** of the second semiconductor layer **25** is lower than the second conduction band **222** of the N-type semiconductor layer **22**, the first electron **271***a* on the second conduction band **222** of the N-type semiconductor layer **22** theoretically cannot directly pass through the second semiconductor layer **25**. However, when the difference in energy between the fourth valence band **251** of the second semiconductor layer **25** and the second conduction band **222** of the N-type semiconductor layer **22** is less than 0.1~0.2 eV, the first electron **271***a* may jump onto the fourth valence band **251** of the second semiconductor layer **25** by phonon collision, where it is conducted to the external circuit **28** through the fourth valence band **251** or an energy-level channel.

In addition, as for the higher-energy third electron **273***a* and the lower-energy fourth electron **274***a* that are not on the second conduction band **222** of the N-type semiconductor layer **22**, they can also be moved onto the fourth valence band **251** of the N-type semiconductor layer **22** by energy redistribution, and jump onto the fourth valence band **251** of the second semiconductor layer **25** through phonon collision, thereby allowing both the third electron **273***a* and the fourth electron **274***a* to be conducted to the external circuit **28** via the fourth valence band **251** or an energy-level channel.

From FIGS. **3**A and **4**B above, it can be seen that the hot-carrier photoelectric conversion device **2'** of the present invention may choose the appropriate N-type semiconductor layer **22** and second semiconductor layer **25** for collecting electrons (hot carriers).

In FIGS. **4**A and **4**B, the redistribution of energy can be applied to both the electrons and the holes at the same time, or to just the electrons or the holes. As electrons are generally spread across a wider energy range, energy redistribution is usually applied to electrons in actual practice, thus allowing the hot-carrier photoelectric conversion device **2'** to create more hot carriers (electrons).

FIG. **5** shows a schematic diagram of a hot-carrier photoelectric conversion device **2"** and the photoelectric conversion method thereof according to a third embodiment of the present invention. As shown in FIG. **5**, the hot-carrier photoelectric conversion device **2"** may include a P-type electric field enhancing level **23***a* and an N-type electric field enhancing level **23***b*.

The material of the P-type electric field enhancing level **23***a* can be MoO_3 or MoO_x. It can be formed between the P-type semiconductor layer **21** and the inorganic conducting light-absorbing layer **23** for enhancing the intensity of the internal electric field between the P-type semiconductor layer **21** and the inorganic conducting light-absorbing layer **23**, allowing hot carriers such as the first hole **271***b* and the like to be quickly separated to the P-type semiconductor layer **21**.

The material of the N-type electric field enhancing level **23***b* can be PFN ((poly [(9,9-bis(3'-(N,N-dimethylamino) propyl)-2,7-fluorene)-alt-2,7-(9,9-dioctylfluorene)]. It can be formed between the N-type semiconductor layer **22** and the inorganic conducting light-absorbing layer **23** for enhancing the intensity of the internal electric field between the N-type semiconductor layer **22** and the inorganic conducting light-absorbing layer **23**, allowing hot carriers such as the first electron **271***a* and the like to be quickly separated to the N-type semiconductor layer **22**.

As a result, the hot-carrier photoelectric conversion device **2"** of the present invention is able to create a large amount of hot carriers with a high open-circuit voltage and a high current such as the first electron **271***a* and the first hole **271***b*. These hot carriers such as the first electron **271***a* and the first hole **271***b* are further conducted to the external circuit **28** through the internal electric field, energy-level channels, phonon collision and/or energy redistribution described in FIGS. **2** to **4**B above.

According to the descriptive example of the present invention, the materials for electric field enhancing discussed above may not be MoO_x or PFN. The present invention is not limited to MoO_x or PFN, but can be other materials.

From the above, it can be understood that the hot-carrier photoelectric conversion device and the photoelectric conversion method of the present invention have at least the following advantages.

(1) Since the inorganic conducting light-absorbing layer does not have a bandgap of a P-type or N-type semiconductor layer as that in the prior art, the inorganic conducting

light-absorbing layer of the present invention formed between the P-type semiconductor layer and the N-type semiconductor layer may absorb photons of any wavelengths, thereby increasing the quantity of photons absorbed, so as to create large amounts of electrons and holes.

(2) The thickness of the inorganic conducting light-absorbing layer is very thin—50 nm or less, or smaller than or equal to five times the mean free path of the electrons or holes within the inorganic conducting light-absorbing layer, so that the electrons and holes can be quickly conducted to the external circuit by the electric field or the diffusion effect regardless of their energy. As such, the electrons and the holes can be conducted at a high speed with a large capture and low energy loss, thereby obtaining a large amount of high-energy electrons and holes (hot carriers), and creating electric energy with a high open-circuit voltage and a high current.

(3) A first energy-level channel is formed between the P-type semiconductor layer and the first semiconductor layer, and a second energy-level channel is formed between the N-type semiconductor layer and the second semiconductor layer, so that the electrons and the holes are conducted to the external circuit via the first and the second energy-level channels, respectively. As a result, large amounts of high-energy electrons and holes can be quickly captured, so as to increase photoelectric conversion efficiency and create electric energy with a high open-circuit voltage and a high current.

(4) A P-type electric field enhancing layer and/or an N-type electric field enhancing layer are/is formed on one or both sides of the inorganic conducting light-absorbing layer to enhance the intensity of the internal electric field, so that the hot carriers (holes and electrons) can be quickly separated to the P-type semiconductor layer and the N-type semiconductor layer, respectively.

The above embodiments are only used to illustrate the principles of the present invention, and should not be construed as to limit the present invention in any way. The above embodiments can be modified by those with ordinary skill in the art without departing from the scope of the present invention as defined in the following appended claims.

What is claimed is:

1. A hot-carrier photoelectric conversion method, comprising the steps of:

providing a hot-carrier photoelectric conversion device including a P-type semiconductor layer, an N-type semiconductor layer, and an inorganic conducting light-absorbing layer formed between the P-type semiconductor layer and the N-type semiconductor layer;

absorbing photons by the inorganic conducting light-absorbing layer to create electrons and holes; and

shifting the electrons and holes to the N-type semiconductor layer and the P-type semiconductor layer by an electric field or diffusion, respectively, so that the electrons and the holes are respectively conducted outside to create electric energy with a portion of the electric energy being transferred from higher-energy hot carriers to lower-energy hot carriers through carrier collisions before hot carriers are shifted out of the hot-carrier photoelectric conversion device through the P-type semiconductor layer and the N-type semiconductor layer.

2. The hot-carrier photoelectric conversion method of claim **1**, wherein at least one of the P-type semiconductor layer and the N-type semiconductor layer is a transparent or partially transparent semiconductor layer for the photons to pass through the transparent or partially transparent semiconductor layer to the inorganic conducting light-absorbing layer so as to create electrons and holes.

3. The hot-carrier photoelectric conversion method of claim **1**, wherein both the P-type semiconductor layer and the N-type semiconductor layer are inorganic semiconductor layers or organic semiconductor layers, or one of the P-type semiconductor layer and the N-type semiconductor layer is an inorganic semiconductor layer and the other one is an organic semiconductor layer.

4. The hot-carrier photoelectric conversion method of claim **1**, wherein the inorganic conducting light-absorbing layer is made of a metal, graphite or graphene.

5. The hot-carrier photoelectric conversion method of claim **1**, wherein the inorganic conducting light-absorbing layer has a thickness of less than 50 nm, or no more than five times a mean free path of the electrons or the holes within the inorganic conducting light-absorbing layer.

6. The hot-carrier photoelectric conversion method of claim **1**, further comprising forming a first semiconductor layer on the P-type semiconductor layer, or between the P-type semiconductor layer and the inorganic conducting light-absorbing layer to create a first energy-level channel between a conduction band of the first semiconductor layer and a valence band of the P-type semiconductor layer, so as for the holes to be conducted to an external circuit through the first energy-level channel, wherein the conduction band of the first semiconductor layer has an energy level lower than an energy level of the valence band of the P-type semiconductor layer.

7. The hot-carrier photoelectric conversion method of claim **6**, wherein when the energy of the holes is greater than the energy level of the first energy-level channel, the energy of the holes meets the energy level of the first energy-level channel through energy redistribution, so that the holes are able to pass through the first energy-level channel.

8. The hot-carrier photoelectric conversion method of claim **1**, further comprising forming a second semiconductor layer on the N-type semiconductor layer, or between the N-type semiconductor layer and the inorganic conducting light-absorbing layer to create a second energy-level channel between a valence band of the second semiconductor layer and a conduction band of the N-type semiconductor layer, so as for the electrons to be conducted to an external circuit through the second energy-level channel, wherein an energy level of the valence band of the second semiconductor layer is higher than an energy level of the conduction band of the N-type semiconductor layer.

9. The hot-carrier photoelectric conversion method of claim **8**, wherein when an energy of the electrons is greater than an energy level of the second energy-level channel, the energy of the electrons meets the energy level of the second energy-level channel through energy redistribution, so that the electrons are able to pass through the second energy-level channel.

10. The hot-carrier photoelectric conversion method of claim **1**, further comprising forming a first semiconductor layer on the P-type semiconductor layer, or between the P-type semiconductor layer and the inorganic conducting light-absorbing layer, wherein an energy level of a conduction band of the first semiconductor layer is higher than an energy level of a valence band of the P-type semiconductor layer, and an energy difference between the conduction band of the first semiconductor layer and the valence band of the P-type semiconductor layer is less than 0.2 eV.

11. The hot-carrier photoelectric conversion method of claim **1**, further comprising forming a second semiconductor layer on the N-type semiconductor layer, or between the N-type semiconductor layer and the inorganic conducting light-absorbing layer, and an energy level of a valence band of the second semiconductor layer is lower than an energy level of a conduction band of the N-type semiconductor layer, and an energy difference between the valence band of the second semiconductor layer and the conduction band of the N-type semiconductor layer is less than 0.2 eV.

12. The hot-carrier photoelectric conversion method of claim **1**, further comprising forming a P-type electric field enhancing layer between the P-type semiconductor layer and the inorganic conducting light-absorbing layer.

13. The hot-carrier photoelectric conversion method of claim **1**, further comprising forming an N-type electric field enhancing layer between the N-type semiconductor layer and the inorganic conducting light-absorbing layer.

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