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(54) **SPECTRALLY ADAPTIVE MULTIJUNCTION PHOTOVOLTAIC THIN FILM DEVICE AND METHOD OF PRODUCING SAME**

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(57) **ABSTRACT**

A method is provided for converting optical energy to electrical energy in a spectrally adaptive manner. The method begins by directing optical energy into a first photovoltaic module that includes non-single crystalline semiconductor layers defining a junction such that a first spectral portion of the optical energy is converted into a first quantity of electrical energy. A second spectral portion of the optical energy unabsorbed by the first module is absorbed by a second photovoltaic module that includes non-single crystalline semiconductor layers defining a junction and converted into a second quantity of electrical energy. The first quantity of electrical energy is conducted from the first module to a first external electrical circuit along a first path. The second quantity of electrical energy is conducted from the second module to a second external electrical circuit along a second path that is in parallel with the first path.

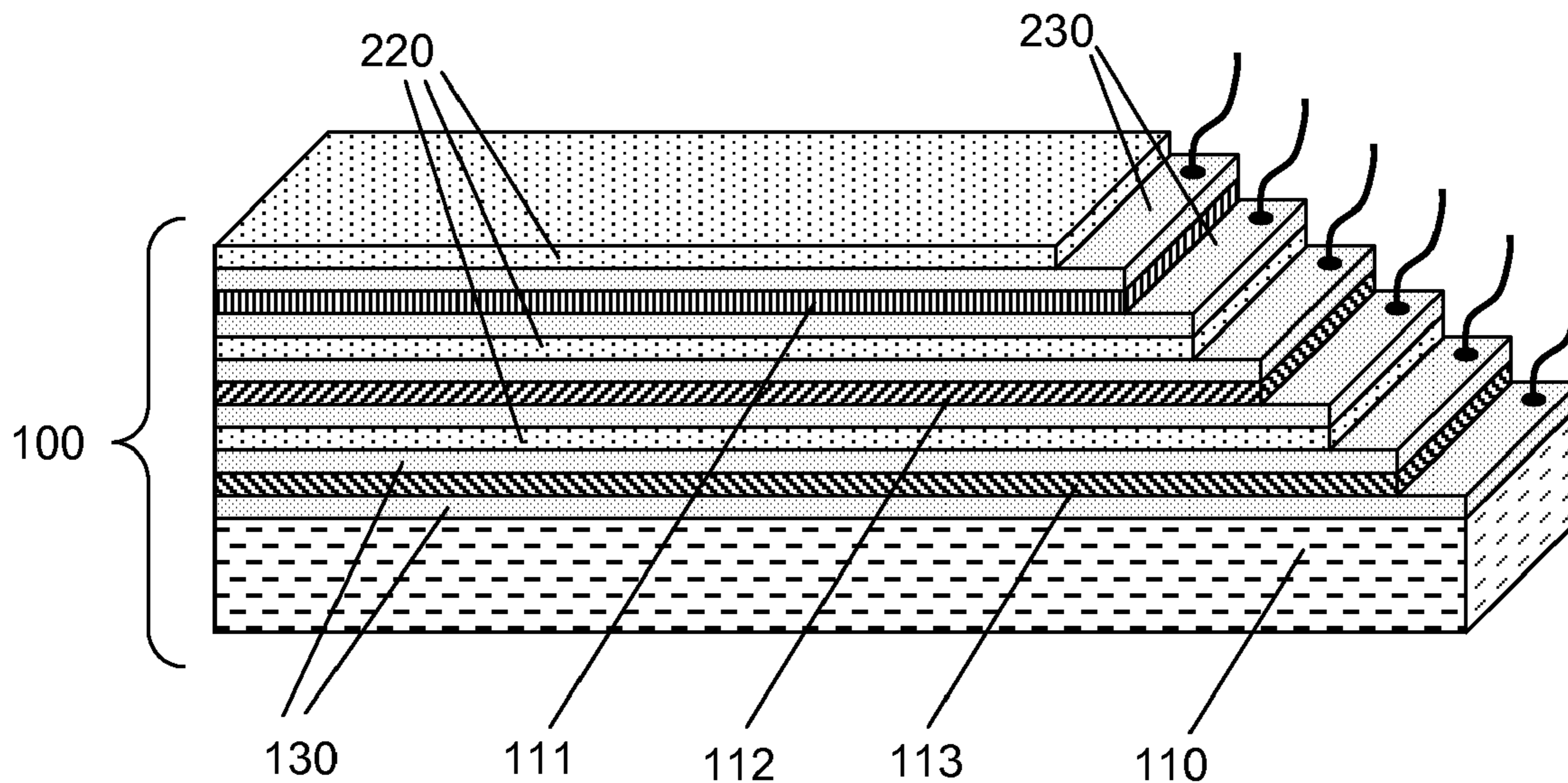
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Related U.S. Application Data

(62) Division of application No. 11/714,681, filed on Mar. 6, 2007, now abandoned.



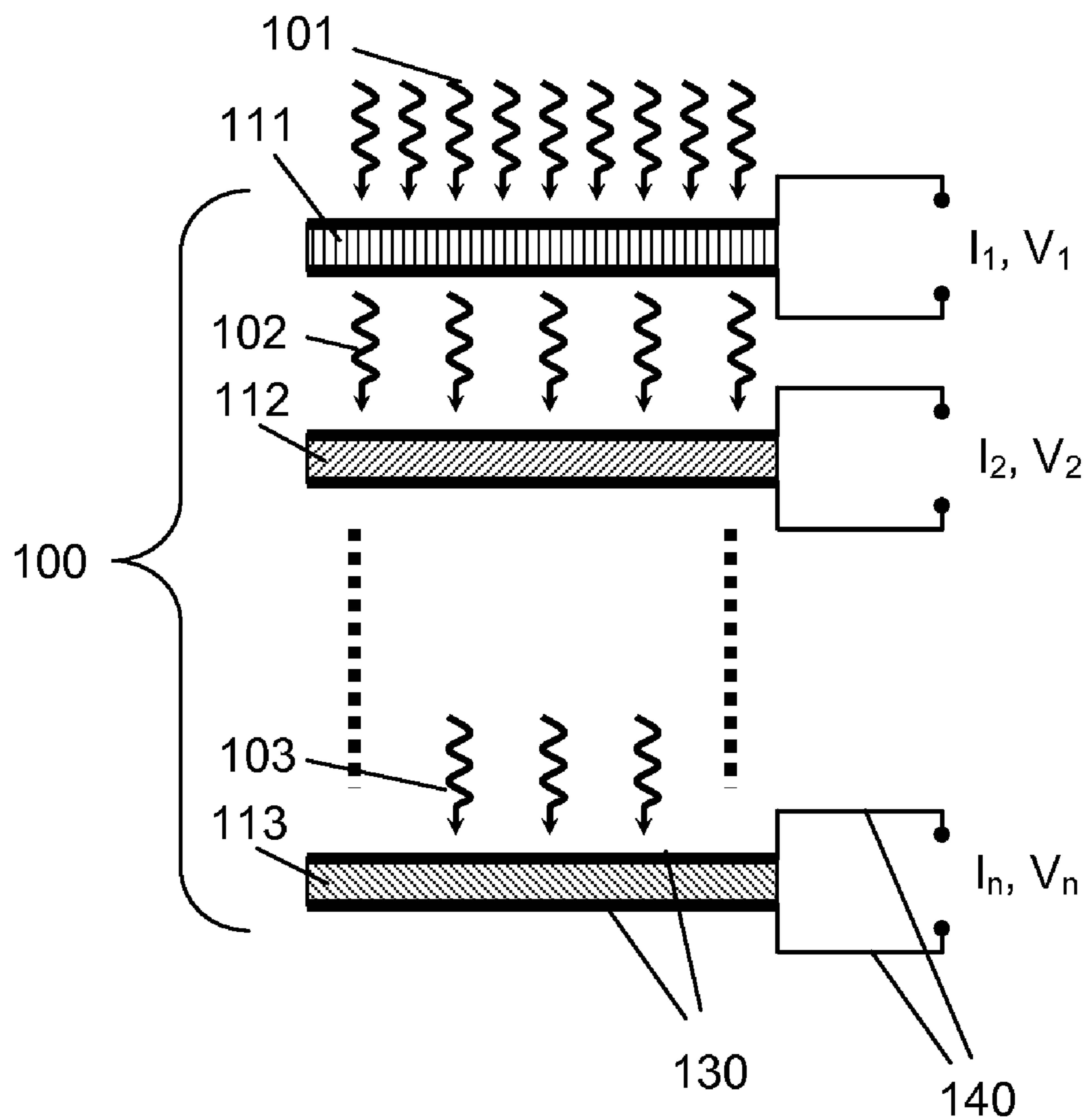


FIG. 1

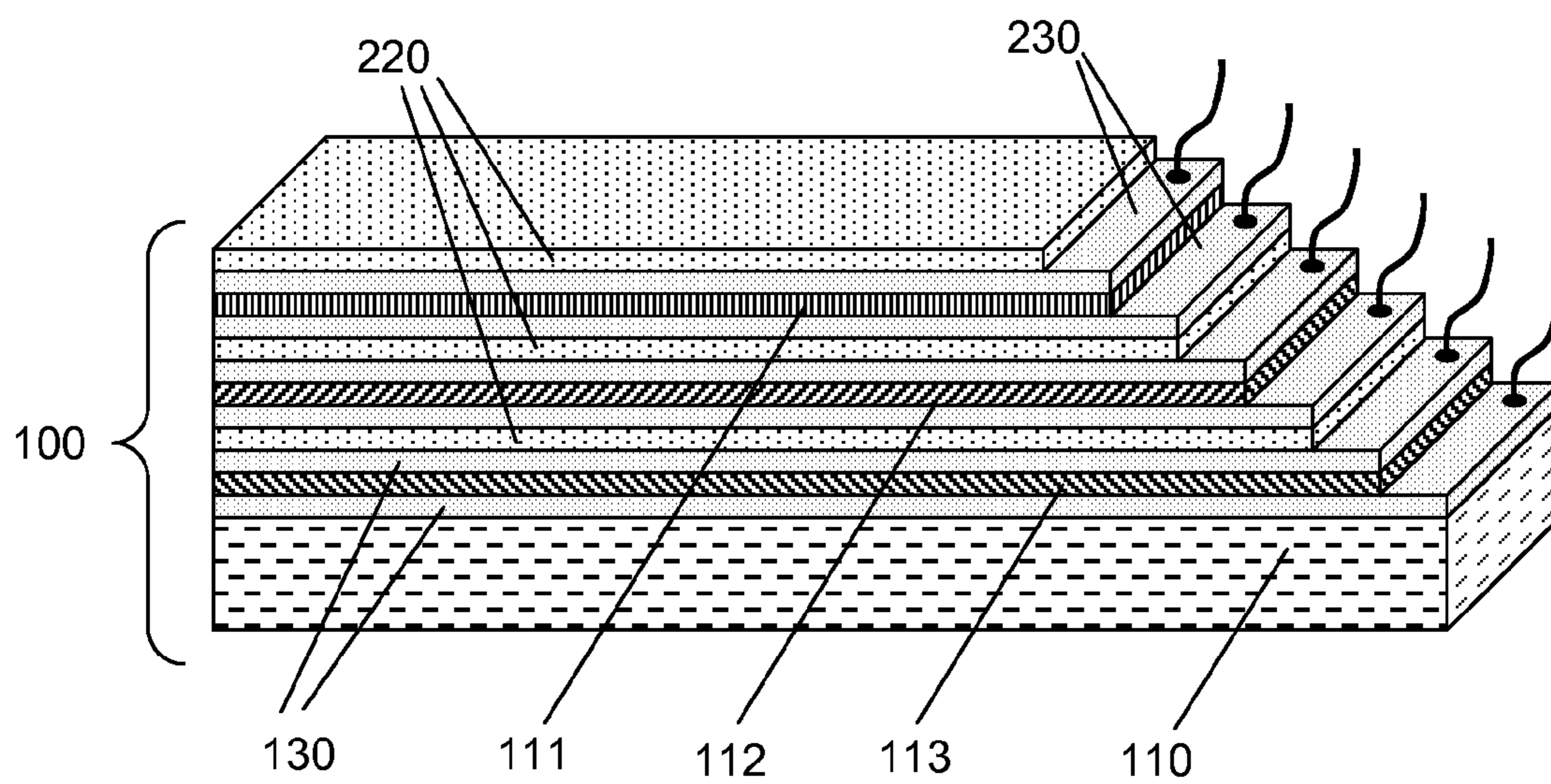


FIG. 2

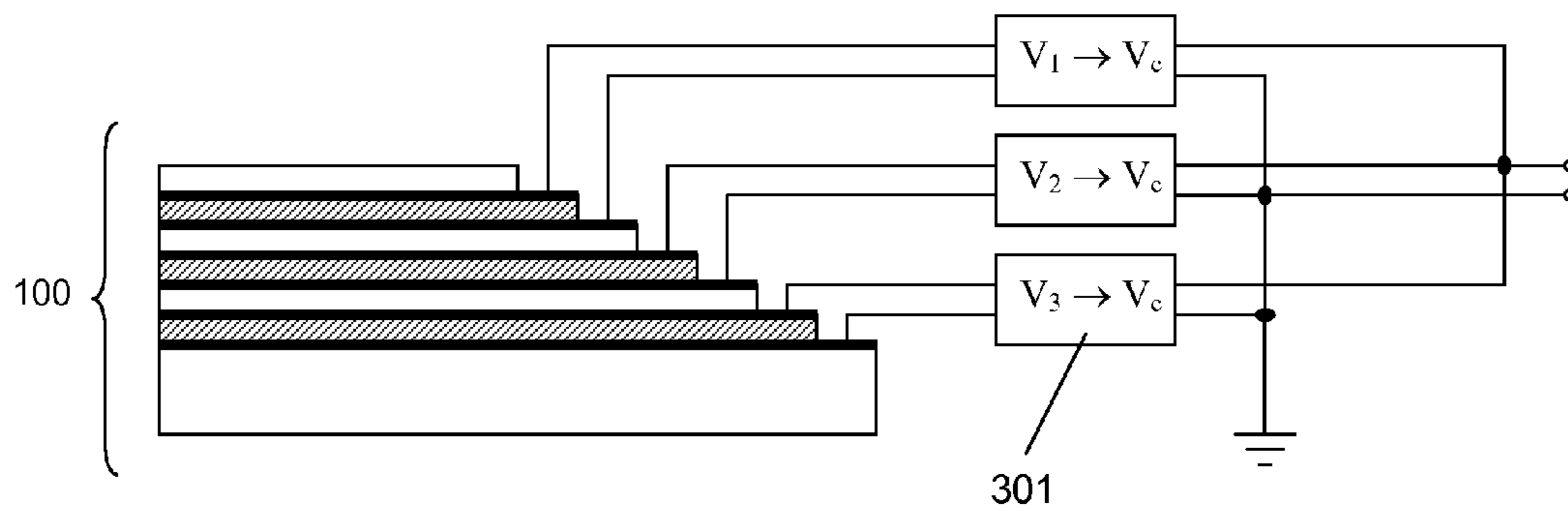


FIG. 3

**SPECTRALLY ADAPTIVE MULTI-JUNCTION
PHOTOVOLTAIC THIN FILM DEVICE AND
METHOD OF PRODUCING SAME**

CROSS REFERENCE TO RELATED
APPLICATION

[0001] This application claims the benefit of co-pending U.S. patent application Ser. No. 11/714,681, filed Mar. 6, 2007, which is incorporated herein by reference in its entirety.

BACKGROUND

[0002] 1. Field

[0003] The following relates to photovoltaic devices and methods of producing such devices. More particularly, the following relates to photovoltaic devices that have substantially improved optical spectral responsivity and efficiency, and that can be produced by laminating or otherwise integrating multiples of discrete photovoltaic devices.

[0004] 2. Related Art

[0005] Photovoltaic devices represent one of the major sources of environmentally clean and renewable energy. They are frequently used to convert optical energy into electrical energy. Typically, a photovoltaic device is made of one semiconductor material with p-doped and n-doped regions. The conversion efficiency of solar power into electricity of this device is limited to a maximum of about 37%, since photon energy in excess of the semiconductor's bandgap is wasted as heat. A photovoltaic device with multiple semiconductor layers of different bandgaps is more efficient: an optimized two-bandgap photovoltaic device has the maximum solar conversion efficiency of 50%, whereas a three-bandgap photovoltaic device has the maximum solar conversion efficiency of 56%. Realized efficiencies are typically less than theoretical values in all cases.

[0006] Multi-layered or multi junction devices are currently manufactured as monolithic wafers, where each semiconductor layer is crystal-grown on top of the previous one. As a result, the semiconductor layers are electrically connected in series and have to be current-matched, in order to obtain maximum conversion efficiency. This current-matching procedure complicates the design and decreases the efficiency of the device. The latter becomes particularly evident when considering the effect of spectral filtering on the device efficiency. If a part of the solar spectrum is absorbed or scattered, e.g. by water vapors, the resulting disproportional decrease of photocurrent in one of junctions will limit the current through the whole device and thus decrease its conversion efficiency.

SUMMARY

[0007] An apparatus for spectrally adaptive photovoltaic energy conversion device, insensitive to current matching effects, and a method for producing the same are provided. The apparatus includes a substrate, a plurality of thin-film single junction photovoltaic layers disposed on said substrate and a plurality of electrical contacts to each of said layers. The plurality of photovoltaic layers may be semi-conducting and have different respective bandgaps so as to increase the conversion efficiency of the device. The said layers may further be at least partially transparent in the spectral energy range below their respective bandgaps. The said layers may further be electrically isolated from each other. The plurality of electrical contacts is arranged to receive independent electrical

currents from each of the photovoltaic layers, so as to further increase conversion efficiency and provide spectrally adaptive capabilities of a device with respect color and intensity variations in incident or absorbed light.

[0008] In accordance with another aspect of the invention, a method is provided for converting optical energy to electrical energy in a spectrally adaptive manner. The method begins by directing optical energy into a first photovoltaic module that includes non-single crystalline semiconductor layers defining a junction such that a first spectral portion of the optical energy is converted into a first quantity of electrical energy. A second spectral portion of the optical energy unabsorbed by the first module is absorbed by a second photovoltaic module that includes non-single crystalline semiconductor layers defining a junction and converted into a second quantity of electrical energy. The first quantity of electrical energy is conducted from the first module to a first external electrical circuit along a first path. The second quantity of electrical energy is conducted from the second module to a second external electrical circuit along a second path that is in parallel with the first path.

[0009] In accordance with another aspect of the invention, a method is provided for converting optical energy with a given spectral profile to electrical energy. The method begins by receiving optical energy on an uppermost module of a photovoltaic device that includes a plurality of modules stacked one on top of another. A first spectral portion of the optical energy is converted to electrical energy. The uppermost module has a first fill factor determined in part by the given spectral profile of the first spectral portion of the optical energy. A remaining portion of the optical energy is transferred to a second module located below the uppermost module. At least a fraction of the remaining portion of the optical energy is converted to electrical energy. The second module has a second fill factor largely independent of the first fill factor of the uppermost module and determined in part by the given spectral profile of the remaining spectral portion of the optical energy.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. 1 is a schematic diagram of a thin-film multi junction photovoltaic device with spectrally adaptive capabilities.

[0011] FIG. 2 is a cross-section of a multi-layered multi junction photovoltaic thin film stack.

[0012] FIG. 3 is a schematic diagram for external electrical connections providing a single voltage electrical terminal.

DETAILED DESCRIPTION

Overview

[0013] In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of exemplary embodiments or other examples described herein. However, it will be understood that these embodiments and examples may be practiced without the specific details. In other instances, well-known methods, procedures, components and circuits have not been described in detail, so as not to obscure the following description. Further, the embodiments disclosed are for exemplary purposes only and other embodiments may be employed in lieu of, or in combination with, the embodiments disclosed.

[0014] As summarized above and described in more detail below, the apparatus for spectrally adaptive photovoltaic

energy conversion device and the method for producing the same is provided. Embodiments of this apparatus and method may facilitate the ability to efficiently and economically convert electro-magnetic energy in the form of light into electrical energy in the form of electrical current. Embodiments of this apparatus and method may also facilitate large volume production and widespread usage of photovoltaic devices.

[0015] This invention utilizes thin-film technology as an alternative method of producing a multi junction photovoltaic device. As well known in the art, multi junction devices in general are a more efficient means for conversion solar energy into electricity. However, the development of these devices is currently hindered by the complexity of semiconductor manufacturing processes and their high cost. On the other hand, thin-film processing is substantially less complex and expensive. Using new design approaches and thin-film technology, a new efficient photovoltaic device with expanded capabilities and application range can be produced.

[0016] Typically, single-crystal semiconductors are grown epitaxially, layer-by-layer on a monolithic wafer. Thin-film materials, in contrast, depending on their chemical origin can be deposited and layered by a variety of different methods, using for example evaporation, sputtering, spraying, inkjet printing etc., some of which could be very inexpensive. Furthermore, some thin-film layers can be produced separately and then integrated hybridly using bonding, lamination and other similar methods. Alternatively, in some cases the entire structure may be sequentially grown without the need for any mechanical integration of the individual layers. This flexibility in a manufacturing method makes it possible to implement new design approaches in producing a better photovoltaic device.

[0017] Specifically, a multi-layered and multi junction photovoltaic device **100** may be produced as shown in FIG. 1, in which each junction layer (**111**, **112** and **113**) includes a single junction with an optically active semiconductor having a specific bandgap. Of course, each so-called junction layer includes at least two sublayers that define a junction at their interface. The junction may be a heterojunction in which the sublayers are formed of dissimilar materials. Alternatively, the junction may be of any type known in the art such as, but not limited to, p-i-n junctions, MIS junctions and the like. The number of junction layers, *n*, may be larger than two. Also, the semiconductor material may be, for example, a compound semiconductor formed from an inorganic, polymer-based material, an organic dye-based material, a nanoparticle composite material, a quantum dot composite material, or a mixture of the above materials. Said junction layers are situated in a stack one above another in said multi-layered device. When this photovoltaic device is illuminated by light **101**, each one of its junction layers may absorb a part of light with photon energies above a corresponding bandgap and transmit a part of light with photon energies below a corresponding bandgap (**102** and **103**). These junction layers may be arranged so that the bandgaps of lower lying junctions are smaller than the bandgaps of higher lying junctions; this condition improves the conversion efficiency of the device. Furthermore, these junction layers may be electrically isolated from each other and provided with at least two individual electrical contacts **130** of opposite polarity for producing electrical current. All the junction layers may be attached to a common substrate that may be sturdy yet flexible. The substrate also may be coated with a reflective layer. One or more surfaces in this device could be textured to provide a relief pattern for mul-

multiple light reflections and scattering, which increase absorption length and improve conversion efficiency.

[0018] Thin-film technology greatly simplifies the production of a multi-junction, non-single crystalline (e.g., polycrystalline, amorphous) photovoltaic device. Furthermore, it enables the production of large area, single-sheet, photovoltaic multi junction devices. The latter is not possible using a standard single-crystal semiconductor technology due to the typically limited and small size of semiconductor wafers. Thin-film layers formed from various compound semiconductors may be manufactured as large sheets and laminated, or otherwise joined, together to form a single large area, low-cost device. Moreover, one may define a figure-of-merit for a photovoltaic device as the ratio of its conversion efficiency to the manufacturing cost per unit area:

$$a. FOM = \text{Efficiency/Cost} \quad (1)$$

[0019] One may also see using Eq.1, that thin-film non-single crystalline multi junction devices will provide the highest attainable FOM. Indeed, their conversion efficiency is estimated to be in the range of 30% to 50% and comparable to that of a single crystal multi junction device, whereas a single junction thin-film photovoltaic device has efficiency of less than 20%. Yet at the same time, their manufacturing cost is estimated to be two orders of magnitude lower than that of a single crystal multi junction device. Thus, it is estimated that FOM of thin-film multi junction devices could be about 100 times larger than that of a single crystal multi junction device and 3-5 times larger than that of a single junction thin-film device.

[0020] Current approaches to the design of multi junction devices usually result in production of serially connected junctions. As a result, an electrical current through each junction must be the same; this is a condition called current matching and it is accomplished by careful selection of semiconductor bandgaps and layer thicknesses given a predetermined shape of the light spectrum. This current matching unduly complicates the design of the device, reduces its fault tolerance and may also reduce its conversion efficiency. For example, a failure of one junction will result in a failure of the whole device. Furthermore, under changing environmental conditions the spectrum of light used for energy conversion may change substantially. This effect may in turn lead to disproportionately different changes of current in different junctions, thus breaking the current matching condition and reducing conversion efficiency. For example, if an increase of moisture content in terrestrial atmosphere leads to 50% reduction of infrared portion of sunlight optical energy due to optical filtering effect, then a typical single crystal multi junction device with Ge as a bottom layer active material may experience an overall 50% reduction in its output current. In this situation the bottom-most junction will limit the current provided by the whole device because the current in the upper junction or junctions cannot exceed this value even though they would be able to do so otherwise. As a result, the fill factor of the upper junction or junctions will be substantially reduced and the overall conversion efficiency of the device will decrease.

[0021] To overcome the problems arising from serially connected junctions, this invention further improves photovoltaic conversion technology by providing separate contact layers **130** and electrical contacts **140** for each junction layer in thin-film multijunction device. Each contact pair **140** acts as a separate, independent photovoltaic source, thus producing *n*

sets of currents and voltages: from I_1 and V_1 , I_2 and V_2 , to I_n and V_n , where n is the number of junctions. This provision eliminates the need for the current matching condition, which in turn results in a simpler design and manufacturing process, a more robust and fault tolerant performance, higher conversion efficiency and an adaptive capability with respect to changes in the spectral content of light used for conversion. More specifically, the latter property of the multijunction photovoltaic device, referred to as spectral adaptation, allows the photovoltaic device to operate at its maximum possible efficiency regardless of any optical filtering effects that may occur during its operation. That is, with spectral adaptation, if the spectral content or profile of the optical energy changes, the conversion efficiency of the device will not decrease to as large an extent as it would if the junctions in the device were required to be current matched. This is because the fill factor of each junction can be largely tailored to the spectral content of the optical energy independent of the other junctions in the device. Also, a failure of any of the thin-film junction layers will not result in failure of the whole device, since they are electrically isolated.

[0022] An additional benefit of this modular manufacturing approach is that a toolbox of individual cell components with different bandgaps could be separately developed and that the set of such cells used in a multijunction device may be specifically selected to maximize the performance for different illumination conditions including AM0 (Space) without any significant change to the manufacturing approach or processing. It is further conceived that a single manufacturing line could be used for a family of products.

Examples

[0023] FIG. 2 shows an exemplary embodiment of this invention, in which three different junction layers **111**, **112** and **113** are utilized. Maximum sunlight power conversion efficiency of this architecture is about 56% for highly concentrated sunbeam and about 50% for regular sunlight intensity (so called condition AM1.5). All three layers contain active polycrystalline semiconductor materials based, for example, on a CIGS (Copper Indium Gallium Selenide) material system or a related alloy, and the corresponding junctions are produced using single junction designs known in the art. By varying the In and Ga relative concentrations the bandgaps in layer **111** may be adjusted to about 1.7 eV, in layer **112**—to about 1.4 eV and in layer **113**—to about 1.1 eV. The thickness of each layer may be in the range of 1 to 10 microns. Each junction layer may also contain buffer layers, such as, for example, a thin CdSe layer with a thickness in the range of 10 to 1000 nm. Each junction layer may be located between appropriately matched transparent conducting layers **130**. The conducting layers **130** may be formed from thin layers of ITO or ZnO with a thickness in the range of 0.1 to 5 μm . Adjacent conducting layers may be separated by an electrical insulator layer **220**, which is optically transparent in the appropriate spectral range. For example, electrically insulating layers may comprise thin films of polymer coating with a thickness in the range of 0.5 to 10 microns. For purposes of clarity in what follows, each junction layer (e.g., junction layers **111**, **112** and **113**) along with its associated conducting layer from time to time may be referred to as a single module. That is, the photovoltaic device shown in FIG. 2 is formed from three such modules.

[0024] The various modules shown in FIG. 2 may be laminated together on a common carrier substrate **110**, such as a

thin polyimide film with a thickness in the range of 25 to 500 microns. The substrate may be coated with metal such as Al to reflect unabsorbed light back into the individual junction modules. The junction modules may be staggered or laterally offset from one another so that each conducting layer **130** has an exposed region **230**. The exposed regions **230**, which may be covered with metal to provide better conductivity, serve as surfaces that can connect the modules to external electrical circuits. As a result, the three modules shown in the device of FIG. 2 may have up to six electrical output connectors.

[0025] In another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that the bandgaps of junction layers **111**, **112** and **113** are 1.8 eV, 1.2 eV and 0.8 eV, respectively. This bandgaps selection is close to the optimum set of three bandgaps for a multijunction photovoltaic device with optimized conversion efficiency.

[0026] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that the active semiconducting material used in producing one or more junction layers is other than the CIGS-based material. This material may be for example CdTe. In another version of this embodiment this material may be a semiconducting polymer material, such as for example polyphenylene-vinylene and its derivatives. A variety of other known and previously mentioned semiconducting materials may be chosen without departing from the scope of the invention.

[0027] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that the substrate is transparent and is attached on the top of the first junction layer **111**.

[0028] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that said junction layers are attached to individual insulating and transparent substrates providing mechanical support such that the common substrate is not necessary.

[0029] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that three of electrical output connectors may be shorted or connected to the ground without loss of device functionality.

[0030] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that additional junction layers with different bandgaps may be laminated with additional individual electrical contacts. In this embodiment the total number of junctions and bandgaps may be greater than four, and the bandgap values are chosen to maximize device conversion efficiency for a given number of junctions.

[0031] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that said junction layers may be produced on separate sacrificial substrates and detached from these substrate before or during the lamination process.

[0032] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that said junction layers may be bonded together to produce a single multi-layered photovoltaic film.

[0033] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that said junction layers may be glued together to produce a single multi-layered photovoltaic film.

[0034] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modi-

fied, so that intermediate insulating material may have a refractive index matched to the surrounding layers, in order to minimize light reflections at layer interfaces in appropriate regions of the optical spectrum.

[0035] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that said conducting layers 130 may be covered with a patterned grid of highly conductive metal, such as Cu or Al, to decrease electrical resistance of the corresponding contact layers without substantial decrease in optical transmissivity of the corresponding contact layers.

[0036] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that the reflective surface of the bottom substrate may be textured so that reflected light is scattered and absorbed by junction layers more efficiently.

[0037] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that the bottom substrate may be textured and non-uniform so as to provide a textured and non-uniform pattern for all junction layers in order to increase light absorption by junction layers.

[0038] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that the bottom substrate may be transparent and its bottom surface may be reflective and textured in order to increase light scattering and absorption.

[0039] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that the multi-layered multijunction film has an area larger than 400 cm².

[0040] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that at least one electrical contact pair from a junction layer is connected to an individual electrical grid which improves conversion efficiency of the whole photovoltaic film.

[0041] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that each electrical contact pair from corresponding junction layers is connected to an individual electrical grid which improves conversion efficiency of the whole photovoltaic film.

[0042] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that each electrical contact pair from corresponding junction layers is connected to a DC-to-DC voltage converter.

[0043] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that each electrical contact pair from corresponding junction layers is connected to a DC-to-AC voltage converter.

[0044] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that each electrical contact pair from corresponding junction layers is connected to a voltage converter. Each voltage converter 301 may convert a different junction voltage to a common voltage, so that all junction layers may be connected in parallel without loss of functionality as shown in FIG. 3 thus providing only two output terminals.

[0045] In yet another embodiment, the apparatus and method described above and shown in FIG. 2 may be modified, so that said junction layers are subdivided into different sections and electrically connected in series to provide a higher output voltage.

[0046] Variations of the apparatus and method described above are possible without departing from the scope of the invention.

What is claimed is:

1. A spectrally adaptive photovoltaic device, comprising: a plurality of photovoltaic modules disposed one on top of another, each of the modules including first and second conductive layers and at least first and second semiconductor layers disposed between the conductive layers, said first and second semiconductor layers defining a junction at an interface therebetween; said first and second semiconductor layers of at least one of the modules being non-single crystalline, thin-film layers; a substrate on which the plurality of photovoltaic modules are stacked; an insulating layer disposed between adjacent photovoltaic modules; and wherein at least one of the junctions is configured to convert a first spectral portion of optical energy into an electrical voltage and transmit a second spectral portion of optical energy to another of the junctions that is configured to convert the second spectral portion of optical energy into an electrical voltage.
2. A device of claim 1 wherein the plurality of modules includes at least three modules.
3. A device of claim 1 wherein the plurality of junctions collectively have a solar energy conversion efficiency of greater than about 20%.
4. A device of claim 1 where at least two of the junctions have semiconductor bandgaps that are different from each other.
5. A device of claim 4 where said junction with a smaller bandgap is disposed below another of junction with a larger bandgap and absorbs said second part of optical energy.
6. A device of claim 1 where said modules are laterally displaced from one another in part to thereby expose a portion of each of the conductive layers.
7. A device of claim 1 where said semiconductor layers comprise CIGS-based semiconductor materials.
8. A device of claim 1 where said semiconductor layers comprise Cd-based semiconductor materials.
9. A device of claim 1 where said semiconductor layers comprise semiconducting polymers.
10. A device of claim 1 where said semiconductor layers comprise nanoparticle composite materials.
11. A device of claim 1 where said semiconductor layers comprise organic composite materials.
12. A device of claim 1 where said semiconductor layers comprise amorphous semiconductor materials.
13. A device of claim 1 wherein the semiconductor layers of at least one of the modules comprise a compound semiconductor material.
14. A device of claim 1 where said first and second conductive layers comprise transparent conducting layers.
15. A device of claim 1 where said insulating layer comprises a transparent insulating layer.
16. A device of claim 1 further comprising a reflecting coating located between a bottommost junction and the substrate.
17. A device of claim 1 further comprising a textured surface for scattering unabsorbed part of said optical energy.

18. A device of claim **1** wherein a fill factor of a module remote from the substrate is largely independent of a fill factor of a module closer to the substrate.

19. A device of claim **1** where said modules are hybridly attached to each other.

20. A device of claim **1** where said modules are laminated to each other.

21. A device of claim **1** where said modules are bonded to each other.

22. A device of claim **1** wherein each module has an area larger than about 400 cm².

23. A device of claim **1** further comprising a plurality of electrical voltage converters coupled to the conductive layers for converting different voltages from different junctions to a single common voltage.

24. A device of claim **1** wherein a conversion efficiency of the device is less dependent on the spectral content of said optical energy than a corresponding device in which current matching is applicable.

25. A method of forming a spectrally adaptive photovoltaic device, comprising:

forming on a substrate a first photovoltaic module that includes first and second conductive layers and at least first and second semiconductor layers disposed between the first and second conductive layers, said first and second semiconductor layers defining a first junction at an interface therebetween such that the first junction converts a first spectral portion of optical energy into an electrical voltage;

forming an insulating layer over the first photovoltaic module; and

forming on the insulating layer a second photovoltaic module that includes third and fourth conductive layers and at least third and fourth semiconductor layers disposed between the third and fourth conductive layers, said third and fourth semiconductor layers defining a second junction at an interface therebetween such that the second junction converts a second spectral portion of optical energy into an electrical voltage.

26. The method of claim **25** wherein said modules are initially produced on different sacrificial substrates.

27. The method of claim **25** further comprising independently selecting values of output voltages and currents for each of said photovoltaic modules to enhance their respective individual fill factors, wherein said values of output voltages and currents depend at least on part on a spectral profile of said optical energy.

28. The method device of claim **25** where said modules are hybridly attached to each other.

29. The method of claim **25** where said modules are laminated to each other.

30. The method of claim **25** where said modules are bonded to each other.

31. The method of claim **25** wherein each module has an area larger than about 400 cm².

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