PHOTOVOLTAIC DEVICE WITH CONTAINER COMPRISING VOLUME COMPENSATION

CROSS REFERENCE TO RELATED APPLICATION

This application claims benefit of U.S. Provisional Patent Application No. 60/926,901, filed on April 30, 2007, which is hereby incorporated by reference herein in its entirety. This application also claims benefit of U.S. Patent Application No. 11/998,780, filed on November 30, 2007, which is hereby incorporated by reference herein in its entirety.

BACKGROUND

Figure 1 is a schematic block diagram of a conventional photovoltaic device. A photovoltaic device 10 can typically have one or more solar cells 12 disposed within it. A solar cell conventionally is made by having a semiconductor junction disposed between a layer of conducting material 104 and a layer of transparent conducting material 110. Light impinges upon the solar cells 12 of a photovoltaic module 10 and passes through the transparent conducting material layer 110. Although other designs are possible, a typical semiconductor junction comprises an absorber layer 106 and a window layer 108. Within the semiconductor junction, the photons interact with the material to produce electron-hole pairs. The semiconductor junction is typically doped creating an electric field extending from the junction layer. Accordingly, when the holes and/or electrons are created by the sunlight in the semiconductor junction, they will migrate depending on the polarity of the field either to the transparent conducting material layer 110 or the layer of conducting material 104. This migration creates current within the solar cell 12 that is routed out of the cell for storage and/or concurrent use.

One conducting node of the solar cell 12 is shown electrically coupled to an opposite node of another solar cell 12. In this manner, the current created in one solar cell may be transmitted to another, where it is eventually collected. The currently depicted apparatus in Figure 1 is shown where the solar cells are coupled in series, thus creating a higher voltage device. In another manner, not shown, the solar cells can be coupled in parallel thereby increasing the resulting current rather than the voltage.

As further illustrated in Figure 1, the conducting material 104 is supported by a substrate. Further, an antireflection coating 112 may be disposed on transparent conducting material 110. Solar cells 12 are sealed from the environment by the substrate 102 and the transparent panel 60. Typically, there is a filler layer 5 between the active layers of the solar cell and the transparent panel 60. In some solar cells, there is a filler layer between conducting

material 104 and substrate 102. Typically, this filler layer is made of ethylene-vinyl acetate (EVA). The EVA is applied as a sheet and then heated so that it melts and crosslinks. In this manner, an intermediate layer is formed between the device (layers 104 through 112) and the outer layers 60 and 102. The cured EVA is solid in nature, and has a very low volumetric coefficient of expansion relative to temperature. Accordingly, the EVA is very tolerant in the environment. However, it is hard to apply the EVA in anything other than planar sheets. Thus, for assemblies that are not planar in nature, the application of the EVA is problematic. Further, since the vast majority of solar cells are employed as planar cells, there really is no outstanding need to alter the outer-layer – EVA – device architecture.

Given the above background, what is needed in the art are improved filler layers for photovoltaic devices that can be easily assembled even in the case where the photovoltaic device is based upon a non-planar substrate. Further, what are needed in the art are photovoltaic devices that incorporate such improved filler layers.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated into and constitute a part of this specification, illustrate one or more embodiments of the present disclosure and, together with the detailed description, serve to explain the principles and implementations of the disclosure.

Fig. 1 illustrates interconnected solar cells in accordance with the prior art.

Fig. 2 is a cross-sectional illustration of the layers found in a nonplanar photovoltaic device having a diaphragm.

Fig. 3A illustrates a partial perspective view of a nonplanar photovoltaic device having a diaphragm.

Fig. 3B illustrates a partial perspective view of the nonplanar photovoltaic device of Fig. 3A with a cutaway to further illustrate the diaphragm.

Fig. 3C illustrates a partial perspective view of the nonplanar photovoltaic device of Fig. 3A with all but the hollow inner substrate core and diaphragm removed.

Fig. 3D illustrates a partial perspective view of the nonplanar photovoltaic device of Fig.

3C in which the diaphragm has expanded into the hollow inner substrate core.

Fig. 4A illustrates a planar photovoltaic device with a volume compensation container.

Fig. 4B illustrates a nonplanar photovoltaic device with a plurality of volume compensation containers.

Fig. 5A illustrates a perspective view of a flexible sealed container for volume compensation use in a nonplanar or planar photovoltaic device.

Fig. 5B illustrates a perspective view of a spring loaded type container for volume compensation use in a nonplanar or planar photovoltaic device.

Fig. 5C illustrates a perspective view of a dual spring loaded type container for volume compensation use in a nonplanar or planar photovoltaic device.

Fig. 5D illustrates a perspective view of a collapsible balloon type container for volume compensation use in a nonplanar or planar photovoltaic device.

Fig. 5E illustrates a perspective view of an asteroid type container for volume compensation use in a nonplanar or planar photovoltaic device.

Figs. 5F-5G illustrate a cross-sectional view of an asteroid type container for volume compensation use in a nonplanar or planar photovoltaic device.

Figs. 6A- 6D illustrate semiconductor junctions that are used in various nonplanar solar cells.

Like reference numerals refer to corresponding parts throughout the several views of the drawings. Dimensions are not drawn to scale.

DETAILED DESCRIPTION

This application is directed to improved filler layers for photovoltaic devices that can be easily assembled even in the case where the photovoltaic device is based upon a non-planar

substrate. Further, the application is directed to photovoltaic devices that incorporate such improved filler layers. Photovoltaic device construction methods are provided. In particular, methods for engineering photovoltaic devices that can withstand layers of material with substantially different thermal coefficients of expansion are provided.

In the interest of clarity, not all of the routine features of the implementations described herein are shown and described. It will, of course, be appreciated that in the development of any such actual implementation, numerous implementation-specific decisions must be made in order to achieve the developer's specific goals, such as compliance with application- and business-related constraints, and that these specific goals will vary from one implementation to another and from one developer to another. Moreover, it will be appreciated that such a development effort might be complex and time-consuming, but would nevertheless be a routine undertaking of engineering for those of ordinary skill in the art having the benefit of this disclosure

Referring to Figures 2 and 4A, as used in this specification, a photovoltaic device 10 is a device that converts light energy to electric energy, and contains at least one solar cell 12. A photovoltaic device 10 may be described as an integral formation of one or a plurality of solar cells 12. In some instances, a plurality of solar cells 12 are coupled together electrically in an elongated structure in order form the photovoltaic device. Examples of such photovoltaic architectures are found in United States Patent No. 7,235,736, which is hereby incorporated by reference herein in its entirety. For instance, each solar cell 12 in an elongated photovoltaic device 10 may occupy a portion of an underlying substrate 102 common to the entire photovoltaic device 10 and the solar cells 12 may be monolithically integrated with each other so that they are electrically coupled to each other either in series or parallel. Alternatively, the elongated photovoltaic device 10 may have one single solar cell 12 that is disposed on a substrate. In some embodiments, a photovoltaic device 10 has 1, 2, 3, 4, 5 or more, 20 or more, or 100 or more such solar cells 12 integrated onto a common substrate 102. In general, a photovoltaic device 10 is made of a substrate 102 and a material, operable to convert light energy to electric energy, disposed on the substrate. In certain nonplanar embodiments, such material may circumferentially coat the underlying substrate. In some embodiments, such material constitutes the one or more solar cells 12 disposed on the substrate. The material typically comprises multiple layers such as a conducting material, a semiconductor junction, and a transparent conducting material.

1.1 VOLUME COMPENSATION

Both planar photovoltaic devices 10, such as depicted in Figure 4, and photovoltaic

devices 10 that are nonplanar, such as depicted in crosssection in Figure 2, are encompassed in the present disclosure. In the photovoltaic device 10 of Figure 2, a transparent casing 310 circumferentially covers underlying active layers. In some cases, the photovoltaic device 10 that is nonplanar is cylindrical or tubular as depicted in Figure 2. As used herein, the term "cylindrical" means objects having a cylindrical or approximately cylindrical shape. In fact, cylindrical objects can have irregular shapes so long as the object, taken as a whole, is roughly cylindrical. Such cylindrical shapes can be solid (*e.g.*, a rod) or hollowed (*e.g.*, a tube). As used herein, the term "tubular" means objects having a tubular or approximately tubular shape. In fact, tubular objects can have irregular shapes so long as the object, taken as a whole, is roughly tubular.

Figure 2 illustrates the cross-sectional view of an exemplary embodiment of a photovoltaic device 10 that is nonplanar. The photovoltaic device 10 has a substrate 102. In the nonplanar embodiments exemplified by Figure 2, the substrate 102 has a hollow core that defines a container 25. The container 25 is illustrated, for example, in Figures 3C, 3D, 4A, and 4B. In some embodiments, a flexible diaphragm 50 seals off one end of the hollow core of substrate 102 while the other end of the hollow core is capped. In such embodiments, the container 25 is defined by the hollow core of the substrate 102, the flexible diaphragm 50 at one end of the hollow core, and the cap at the other end of the hollow core. In some embodiments, a flexible diaphragm 50 is used on each end of the hollow core of the substrate 102 to seal the interior core. In such embodiments, the container 25 is defined by the hollow core of the substrate 102, the first flexible diaphragm 50 at one end of the hollow core, and the second flexible diaphragm 50 at other end of the hollow core. In some embodiments, the container 25 has little or no air pressure. In some embodiments, the container 25 is under a complete vacuum. In some embodiments, the container 25 is under less than 20 Torr, less than 40 Torr, less than 100 Torr, or less than 500 Torr of pressure. In some embodiments, the container is filled with an inert gas such as helium, neon, or argon.

The photovoltaic device 10 that is nonplanar can be characterized by a cross-section bounded by any one of a number of shapes other than the circular shape depicted in Figure 2. The bounding shape can be any one of circular, ovoid, or any shape characterized by one or more smooth curved surfaces, or any splice of smooth curved surfaces. The bounding shape can also be linear in nature, including triangular, rectangular, pentangular, hexagonal, or having any number of linear segmented surfaces. Or, the cross-section can be bounded by any combination of linear surfaces, arcuate surfaces, or curved surfaces. As described herein, for ease of discussion only, an omnifacial circular cross-section is illustrated to represent nonplanar embodiments of the photovoltaic device 10. However, it should be noted that any

cross-sectional geometry may be used in a photovoltaic device 10 that is nonplanar in practice.

Referring to Figure 2, a layer of conducting material 104, often referred to as the back electrode, is overlayed on all or a portion of the substrate 102. A semiconductor junction is overlayed on all or a portion of the conducting material 104. Although other designs are possible, a typical semiconductor junction comprises an absorber layer 106 and a window layer 108. Optionally, there is an intrinsic layer (*i*-layer) (not shown) overlayed on all or a portion of the semiconductor junction. A layer of transparent conducting material 110 overlays all or a portion of the semiconductor junction and/or *i*-layer. The conducting material 104, the semiconductor junction 106/108, and the transparent conducting material 110, with or without the intrinsic layer, collectively form a solar cell 12 that is disposed on the substrate 102. A filler layer 330 comprising a sealant overlays the solar cell 12 and seals the solar cell 12 within the inner volume defined by the substrate 102 and the transparent casing 310.

Advantageously, the current solar cell devices 10 employ a gel, resin, non-solid, or otherwise highly viscous matter for the filler composition of the filler layer 330. The material is added to the assembly as a liquid, and allowed to cure to the gel or other viscous non-solid state. However, in this approach, the formed material has a much higher thermal coefficient of expansion than conventional materials such as ethylene-vinyl acetate. Thus, during a typical thermal cycle, one can expect substantial volume changes in the filler layer 330 relative to the use of conventional material for the filler composition of the filler layer 330 such as ethylene-vinyl acetate (EVA). For instance, EVA has a volumetric thermal coefficient of expansion of between 160 and 200 x 10^{-6}/ °C whereas soda lime glass has a volumetric thermal coefficient of expansion of 8.6 x 10^{-6}/ °C. By contrast, the gels, resins, non-solids, or otherwise highly viscous matter used for the filler composition of the filler layer 330 in the present disclosure have a volumetric thermal coefficient of expansion that is greater than 200 x 10^{-6}/ °C. For example, one material that is used for the filler composition of the filler layer 330 in the present disclosure, polydimethylsiloxane (PDMS), has a volumetric temperature coefficient of about 960 x 10^{-6}/ °C. Thus, in some embodiments, the filler layer 330 in the present disclosure has a volumetric thermal coefficient of expansion of greater than 250 x 10^{-6}/ °C, greater than 300 x 10^{-6}/ °C, greater than 400 x 10^{-6}/ °C, greater than 500 x 10^{-6}/ °C, greater than 1000 x 10^{-6}/ °C, greater than 2000 x 10^{-6}/ °C, greater than 5000 x 10^{-6}/ °C, or between 250 x 10^{-6}/ °C and 10000 x 10^{-6}/ °C. In one particular embodiment, Dow Corning 200 fluid, which is composed of linear polydimethylsiloxane polymers and has a volumetric coefficient of expansion of 960 x 10^{-6}/°C, is used for the filler layer 300.

Advantageously, volume compensation of the filler layer 330 layer is provided. In the case of the photovoltaic device 10 that is nonplanar, a diaphragm 50 seals off at least one end of

the hollowed substrate 102 as illustrated in cross section in Figure 2 and partial perspective view in Figures 3A-3D thereby forming a container 25 (Figure 2 and Figures 3C and 3D) with a container volume. Figure 3B illustrates a partial perspective view of the photovoltaic device that is nonplanar of Figure 3A with a cutaway 70 to further illustrate diaphragm 50. Figure 3C illustrates a partial perspective view of the photovoltaic device that is nonplanar of Figure 3A with all but the hollow inner substrate core 102 and diaphragm 50 removed so that the details of the diaphragm 50 and the container 25 are more readily apparent.

The diaphragm 50 is affixed to the end of the inner tube before the liquid laminate that forms the layer 330 is introduced into the assembly. The annular volume between the transparent casing 310 and the active device overlaying the substrate 102 is substantially filled with the substance thereby forming the "layer" 330, which can then cure to a more viscous state.

During a heating cycle, the filler composition forming the filler layer 330 expands. However, the force of expansion is offset by the diaphragm 50, which is forced inward into the container 25 due to the force as depicted in Figure 3D. The resistance of the diaphragm 50 is less than the resistance of the outer end cap (not shown) of the photovoltaic device 10 or the side walls of either the substrate 102 or the transparent casing 300. Thus, the force generated by the expanding volume is directed onto the diaphragm 50. When cooled, the pressure goes down and the diaphragm 50 returns to the lower pressure position depicted in Figures 3A through 3C. Thus, Figure 3 illustrates how a container 25 within an inner volume defined by the substrate 102 and outer the transparent casing 310 is formed. In particular, in Figure 3, the container is found within the hollowed portion of substrate 102. The container 25 is defined by at least one wall (*e.g.*, the interior wall of hollowed substrate 103) and an opening, where the opening is in fluid communication with the filler layer 330. A diaphragm 50 is affixed to the opening of the container 25. The diaphragm 50 seals the container 25 thereby defining a container volume. The diaphragm 50 is configured to increase the container 25 volume when the filler layer 330 thermally contracts as illustrated in Figure 3C. The diaphragm 50 is configured to decrease the container 25 volume when the filler layer 330 thermally expands as illustrated in Figure 3D.

In some embodiments, the diaphragm 50 is a made of rubber, a rubberlike material, a rubber derivative, silicone rubber, or an elastomer. In some embodiments, the diaphragm 50 is made of ethylene propylene diene monomer rubber. In some embodiments, the diaphragm 50 is made of natural rubber, vulcanized rubber, a butadiene-styrene polymer such as GR-S, neoprene, nitrile rubbers, butyl, polysulfide rubber, ethylene-propylene rubber, polyurethane rubber, silicone rubber, gutta-percha, and/or balata. In some embodiments the diaphragm 50 is

made of silicone rubber. Silicone rubber is a rubberlike material having a tensile strength of between 400 lb/in^2 to 700 lb/in^2 (2.78 to 4.85 x 106 N/m^2) elongation. In some embodiments, the diaphragm 50 is made of SILASTIC® silicone rubber (Dow Corning). As used herein, the term "elastomer" is used to describe both natural and synthetic materials which are elastic or resilient and in general resemble natural rubber in feeling and appearance. See, for example, Avallone and Baumeister III, *Marks' Standard Handbook for Mechanical Engineers*, McGraw Hill, 1987, which is hereby incorporated by reference herein. In some embodiments, the diaphragm 50 is made out of a plastic or a rubber. In some embodiments, the diaphragm 50 is made out of high-density polyethylene, low-density polyethylene, polypropylene, cellulose acetate, vinyl, plasticized vinyl, cellulose acetate butyrate, melamine-formaldehyde, polyester, nylon. See, for example, *Modern Plastics Encyclopedia*, McGraw-Hill, which is hereby incorporated by reference herein for its teachings on the aforementioned compounds.

In general, the diaphragm 50 is designed with materials light in resiliency and volume contraction, that do not degrade the chemical components of the filler layer 330, and that can withstand stress and the operating temperature ranges of the solar photovoltaic device 10.

In nonplanar photovoltaic embodiments, a container 25 having a container volume is defined by the substrate 102 and the caps used to seal the substrate. In the embodiment illustrated in Figure 2, one end of the substrate 102 is sealed by a diaphragm 50. The other end of the substrate 102 may also be sealed by a diaphragm 50 thereby defining the container volume. Alternatively, the other end of the substrate 102 may be sealed by a rigid cap, thereby defining the container volume. It is possible for this rigid cap to be an integral piece of the substrate 102. It is also possible for this rigid cap to be a separate piece that fits onto the end of the substrate 102 thereby sealing the interior volume of the substrate 102.

Advantageously, the diaphragm 50 is capable of expanding into the container volume 25 when the photovoltaic device 10 warms during normal operation. This contraction reduces the sealed container 25 volume. In various embodiments, the diaphragm 50 is capable of reducing the container 25 volume by up to 5 percent, up to 10 percent, up to 15 percent, up to 20 percent, up to 25 percent, up to 30 percent, up to 35 percent, or between 2 and 40 percent during operation of the photovoltaic device 10. For example, in one nonlimiting embodiment, when the photovoltaic device 10 is cold, the container volume of the container 25 is Y arbitrary volumetric units, but when the photovoltaic device 10 is heated during normal operation, the container 25 volume is reduced to as little as 0.5Y arbitrary volumetric units, for a fifty percent reduction in volume, because the diaphragm 50 expands into the interior of the container 25.

The above-described volume compensation apparatus can be used in the context of planar substrates 102 such as the one illustrated in Figure 4A. In such embodiments, a bank of

planar solar cells 12 can be constructed and have a preformed container 25 somewhere within the mass making up the active portion as illustrated in Figure 4A. A closed off preformed container 25 having a volume 902 is formed in the cell bank. The preformed container 25 has one or more diaphragms 50 sealing openings to the container as depicted in Figure 4A. The diaphragm 50 can be any or all of the diaphragms described above. In such embodiments, any of the above-identified filler compositions for the filler layer 330 can be used for the filler layer 330 of Figure 4A. Thus, in this way, volume compensation can be undertaken in a planar photovoltaic device. Although only a single preformed container 25 is shown in Figure 4A, it will be appreciated that there can be any number of preformed containers 25 within embodiments of the photovoltaic apparatus 10 that are planar or that are nonplanar. For example, there can be one or more, two or more, three or more, ten or more, or 100 or more preformed containers 25 each having a container volume that is regulated by one or more diaphragms 50 in the manner described above. Each such preformed container 25 may have the same or different geometric shape. The cylindrical shape of the preformed container 25 in Figure 4A is shown simply for the sake of presenting the concept. The cylindrical shape illustrated in Figure 4A represents one of many different three dimensional geometric shapes that the preformed container 25 could adopt. Furthermore, the preformed container 25 may adopt an irregular nongeometric three dimensional shape.

It should also be mentioned that the preformed containers 25 such as those depicted in Figure 4A that are immersed within filler lay 330 can also be present in embodiments where the photovoltaic device 10 is nonplanar. For example, referring to Figure 4B, in addition to or instead of a container 25 within substrate 102, one or more containers 25 may be immersed somewhere in the inner volume 802 defined by the substrate 102 and the transparent casing 310, other than the interior of the substrate 102, such as in the space between the solar cells 12 on the substrate 102 and the transparent casing 310 or at either or both ends of the photovoltaic device 10. As illustrated in Figure 4B, there can be multiple preformed containers 25 in the inner volume 802, even in embodiments where the photovoltaic device 10 is not planar.

Reference will now be made to Figure 5, for examples of containers 25 that can be used in volume compensation in photovoltaic devices 10 in the manner described above. In other words, any of the containers 500, 510, 520, 530, 540, and 550 can serve as a container 25.

Figure 5A illustrates a flexible sealed container 500 for volume compensation use in a nonplanar or planar photovoltaic device 10. In some embodiments, the spacing *s* between each of the ridges 504 is the same. In some embodiments the spacing *s* between one or more of the ridges 504 is different. In some embodiments the spacing *s* between each of the ridges 504 is the same. In some embodiments, the container 500 has a cross-sectional shape, with respect to

axis x, that is round, square, ellliptical, a parallelogram, triangular, polygonal, arcuate, or any other two-dimensional regular or irregular closed form shape. In some embodiments, the container 500 has a cross-sectional shape, with respect to axis x, that is an irregular nongeometric shape. Although depicted as a cylinder in Figure 5A, in some embodiments, the container 500 has any geometric or nongeometric shape, including but not limited to a box, a cone, a sphere, or a cylinder. The container 500 can be made of any flexible material including flexible plastic or thin malleable metal. The flexible sealed container 500 is responsive to changes in the volume of filler layer 330. When a photovoltaic apparatus 10 is operating at high temperatures, all or a portion of the flexible sealed container 500 contracts due to thermal expansion of the filler layer 330. Further, when a photovoltaic apparatus 10 is operating at low temperatures, all or a portion of the flexible sealed container 500 expands due to thermal contraction of the filler layer 330. In various embodiments, the flexible sealed container 500 is capable of a reduction of container volume by up to 5 percent, up to 10 percent, up to 15 percent, up to 20 percent, up to 25 percent, up to 30 percent, up to 35 percent, or between 2 and 40 percent during operation of the photovoltaic device 10. For example, in one nonlimiting embodiment, when the photovoltaic device 10 is cold, the container volume of the container 500 is Y arbitrary volumetric units, but when the photovoltaic device 10 is heated during normal operation, the container 500 volume is reduced to as little as 0.5Y arbitrary volumetric units, for a fifty percent reduction in volume, because the walls of the container 500 collapse into the interior of the container. In some embodiments, the container 500 has little or no air pressure. In some embodiments, the container 500 is under a complete vacuum. In some embodiments, the container 500 is under less than 20 Torr, less than 40 Torr, less than 100 Torr, or less than 500 Torr of pressure. In some embodiments, the container 500 is filled with an inert gas such as helium, neon, or argon. In some embodiments, a container 500 is dimensioned to have a container volume of at least one cubic centimeter, at least 10 cubic centimeters, at least 20 cubic centimeters, at least 30 cubic centimeters, at least 50 cubic centimeters, at least 100 cubic centimeters, or at least 1000 cubic centimeters.

Figure 5B illustrates a spring loaded type container 510 for volume compensation use in a nonplanar or planar photovoltaic device 10. In some embodiments, the container 510 has a cross-sectional shape, with respect to axis x, that is round, square, ellliptical, a parallelogram, triangular, polygonal, arcuate, or any other two-dimensional regular or irregular closed form shape. In some embodiments, the container 510 has a cross-sectional shape, with respect to axis x, that is an irregular nongeometric shape. Although depicted as a cylinder in Figure 5B, in some embodiments, the container 502 has any geometric or nongeometric shape, including but not limited to a box, a cone, a sphere, or a cylinder. In some embodiments, the container 510 is

found in a nonplanar photovoltaic device 10 within the interior of a hollowed substrate 102. The container 510 can be made of any rigid material including nonflexible plastic, glass, or metal. The container 510 has an opening 512 at one end. The opening 512 is sealed by a seal 514. The seal 514 is responsive to changes in the volume of filler layer 330. A spring 516 holds seal 514 in place. In some embodiments, the spring 516 is a metal spring with a spring constant suitable for volume compensation of the filler layer 330. When a photovoltaic apparatus 10 is operating at high temperatures, the spring 516 contracts due to thermal expansion of the filler layer 330. Further, when a photovoltaic apparatus 10 is operating at low temperatures, the spring 516 expands due to thermal contraction of the filler layer 330. In this manner, in various embodiments, the flexible sealed container 510 is capable of a reduction of container volume by up to 5 percent, up to 10 percent, up to 15 percent, up to 20 percent, up to 25 percent, up to 30 percent, up to 35 percent, or between 2 and 40 percent during operation of the photovoltaic device 10. For example, in one nonlimiting embodiment, when the photovoltaic device 10 is cold, the container volume of the container 510 is Y arbitrary units, but when the photovoltaic device 10 is heated during normal operation, the container 510 volume is reduced to as little as 0.5Y arbitrary units, for a fifty percent reduction in volume, because the seal 514 reversibly collapses into the interior of the container. In some embodiments, the container 510 has little or no air pressure. In some embodiments, the container 510 is under a complete vacuum. In some embodiments, the container 510 is under less than 20 Torr, less than 40 Torr, less than 100 Torr, or less than 500 Torr of pressure. In some embodiments, the container 510 is filled with an inert gas such as helium, neon, or argon. In some embodiments, a container 510 is dimensioned to have a container volume of at least one cubic centimeter, at least 10 cubic centimeters, at least 20 cubic centimeters, at least 30 cubic centimeters, at least 50 cubic centimeters, at least 100 cubic centimeters, or at least 1000 cubic centimeters.

Figure 5C illustrates a dual spring loaded type container 520 for volume compensation use in a nonplanar or planar photovoltaic device 10. In some embodiments, the container 520 has a cross-sectional shape, with respect to axis x, that is round, square, ellliptical, a parallelogram, triangular, polygonal, arcuate, or any other two-dimensional regular or irregular closed form shape. In some embodiments, the container 520 has a cross-sectional shape, with respect to axis x, that is an irregular nongeometric shape. Although depicted as a cylinder in Figure 5C, in some embodiments, the container 502 has any geometric or nongeometric shape, including but not limited to a box, a cone, a sphere, or a cylinder. In some embodiments, the container 520 is found in a nonplanar photovoltaic device 10 within the interior of a hollowed substrate 102. The container 520 can be made of any rigid material including nonflexible

plastic, glass, or metal. The container 520 has an opening 512 at each end. Each opening 512 is sealed by a seal 514. The seals 514 are responsive to changes in the volume of filler layer 330. A spring 516 holds each seal 514 in place. In some embodiments, the spring 516 is a metal spring with a spring constant suitable for volume compensation of the filler layer 330. When a photovoltaic apparatus 10 is operating at high temperatures, the springs 516 contract due to thermal expansion of the filler layer 330. Further, when a photovoltaic apparatus 10 is operating at low temperatures, the springs 516 expand due to thermal contraction of the filler layer 330. In this manner, in various embodiments, the flexible sealed container 520 is capable of a reduction of container volume by up to 5 percent, up to 10 percent, up to 15 percent, up to 20 percent, up to 25 percent, up to 30 percent, up to 35 percent, or between 2 and 40 percent during operation of the photovoltaic device 10. For example, in one nonlimiting embodiment, when the photovoltaic device 10 is cold, the container volume of the container 520 is Y arbitrary volumetric units, but when the photovoltaic device 10 is heated during normal operation, the container 520 volume is reduced to as little as 0.5Y arbitrary volumetric units, for a fifty percent reduction in volume, because the seals 514 reversibly collapse into the interior of the container. In some embodiments, the container 510 has little or no air pressure. In some embodiments, the container 520 is under a complete vacuum. In some embodiments, the container 520 is under less than 20 Torr, less than 40 Torr, less than 100 Torr, or less than 500 Torr of pressure. In some embodiments, the container 520 is filled with an inert gas such as helium, neon, or argon. In some embodiments, a container 520 is dimensioned to have a container volume of at least one cubic centimeter, at least 10 cubic centimeters, at least 20 cubic centimeters, at least 30 cubic centimeters, at least 50 cubic centimeters, at least 100 cubic centimeters, or at least 1000 cubic centimeters.

Figure 5D illustrates a collapsible balloon type container 530 for volume compensation use in a nonplanar or planar photovoltaic device 10. The container 530 can be made of any flexible material including, but not limited to, rubber, latex, chloroprene or a nylon fabric. The flexible sealed container 530 is responsive to changes in the volume of filler layer 330. When a photovoltaic apparatus 10 is operating at high temperatures, all or a portion of the flexible sealed container 530 contracts due to thermal expansion of the filler layer 330. Further, when a photovoltaic apparatus 10 is operating at low temperatures, all or a portion of the flexible sealed container 530 expands due to thermal contraction of the filler layer 330. In various embodiments, the flexible sealed container 530 is capable of a reduction of container volume by up to 5 percent, up to 10 percent, up to 15 percent, up to 20 percent, up to 25 percent, up to 30 percent, up to 35 percent, or between 2 and 40 percent during operation of the photovoltaic device 10. For example, in one nonlimiting embodiment, when the photovoltaic device 10 is

cold, the container volume of the container 530 is Y arbitrary volumetric units, but when the photovoltaic device 10 is heated during normal operation, the container 530 volume is reduced to as little as 0.5Y arbitrary volumetric units, for a fifty percent reduction in volume, because the walls of the container 502 collapse into the interior of the container. In some embodiments, the container 530 is under less than 20 Torr, less than 40 Torr, less than 100 Torr, or less than 500 Torr of pressure. In some embodiments, the container 530 is filled with an inert gas such as helium, neon, or argon.

Figure 5E illustrates an asteroid type container 540 for volume compensation use in a nonplanar or planar photovoltaic device 10. The container 540 can be made of any flexible material including flexible plastic, thin malleable metal, or air blown light metal. The flexible sealed container 540 is responsive to changes in the volume of filler layer 330. When a photovoltaic apparatus 10 is operating at high temperatures, all or a portion of the flexible sealed container 540 contracts due to thermal expansion of the filler layer 330. Further, when a photovoltaic apparatus 10 is operating at low temperatures, all or a portion of the flexible sealed container 540 expands due to thermal contraction of the filler layer 330. In various embodiments, the flexible sealed container 540 is capable of a reduction of container volume by up to 5 percent, up to 10 percent, up to 15 percent, up to 20 percent, up to 25 percent, up to 30 percent, up to 35 percent, or between 2 and 40 percent during operation of the photovoltaic device 10. For example, in one nonlimiting embodiment, when the photovoltaic device 10 is cold, the container volume of the container 540 is Y arbitrary volumetric units, but when the photovoltaic device 10 is heated during normal operation, the container 540 volume is reduced to as little as 0.5Y arbitrary volumetric units, for a fifty percent reduction in volume, because the walls of the container 540 collapse into the interior of the container. In some embodiments, the container 540 has little or no air pressure. In some embodiments, the container 540 is under a complete vacuum. In some embodiments, the container 540 is under less than 20 Torr, less than 40 Torr, less than 100 Torr, or less than 500 Torr of pressure. In some embodiments, the container 540 is filled with an inert gas such as helium, neon, or argon. In some embodiments, a container 540 is dimensioned to have a container volume of at least one cubic centimeter, at least 10 cubic centimeters, at least 20 cubic centimeters, at least 30 cubic centimeters, at least 50 cubic centimeters, at least 100 cubic centimeters, or at least 1000 cubic centimeters. In some embodiments, container 540 is not airtight.

Figure 5F illustrates a flexible sealed container 550 for volume compensation use in a nonplanar or planar photovoltaic device 10. The container 540 can be made of any flexible material including flexible plastic or thin malleable metal. The flexible sealed container 540 is responsive to changes in the volume of filler layer 330. When a photovoltaic apparatus 10 is

operating at high temperatures, all or a portion of the flexible sealed container 540 contracts due to thermal expansion of the filler layer 330. Further, when a photovoltaic apparatus 10 is operating at low temperatures, all or a portion of the flexible sealed container 540 expands due to thermal contraction of the filler layer 330. In various embodiments, the flexible sealed container 540 is capable of a reduction of container volume by up to 5 percent, up to 10 percent, up to 15 percent, up to 20 percent, up to 25 percent, up to 30 percent, up to 35 percent, or between 2 and 40 percent during operation of the photovoltaic device 10. For example, in one nonlimiting embodiment, when the photovoltaic device 10 is cold, the container volume of the container 540 is Y arbitrary units, but when the photovoltaic device 10 is heated during normal operation, the container 540 volume is reduced to as little as 0.5Y arbitrary units, for a fifty percent reduction in volume, because the walls of the container 540 collapse into the interior of the container. In some embodiments, the container 540 has little or no air pressure. In some embodiments, the container 540 is under a complete vacuum. In some embodiments, the container 540 is under less than 20 Torr, less than 40 Torr, less than 100 Torr, or less than 500 Torr of pressure. In some embodiments, the container 540 is filled with an inert gas such as helium, neon, or argon. In some embodiments, a container 540 is dimensioned to have a container volume of at least one cubic centimeter, at least 10 cubic centimeters, at least 20 cubic centimeters, at least 30 cubic centimeters, at least 50 cubic centimeters, at least 100 cubic centimeters, or at least 1000 cubic centimeters. Figure 5F illustrates a cross-section of container 550 taken about line 5-5′.

1.2 MATERIALS USED TO MAKE PHOTOVOLTAIC LAYERS

Volume compensation apparatus and techniques have now been described. Reference will now be made to exemplary materials and photovoltaic devices in which the volume compensation techniques can be used. Referring to Figure 2, reference will now be made to each of the exemplary layers in the photovoltaic device 10.

Substrate 102. Substrate 102 serves as a substrate for photovoltaic device 10. In some embodiments, substrate 102 is made of a plastic, metal, metal alloy, or glass. In some embodiments, a length of the substrate 102 is at least three times longer than a width of the substrate. In some embodiments, the substrate 102 has a nonplanar shape. In some embodiments, substrate 102 has a cylindrical shape. In some embodiments, the substrate 102 has a hollow core. In some embodiments, the shape of the substrate 102 is only approximately that of a cylindrical object, meaning that a cross-section taken at a right angle to the long axis of substrate 102 defines an ellipse rather than a circle. As the term is used herein, such approximately shaped objects are still considered cylindrically shaped in the present disclosure.

In some embodiments, the substrate 102 is made of a urethane polymer, an acrylic polymer, a fluoropolymer, polybenzamidazole, polyimide, polytetrafluoroethylene, polyetheretherketone, polyamide-imide, glass-based phenolic, polystyrene, cross-linked polystyrene, polyester, polycarbonate, polyethylene, polyethylene, acrylonitrile-butadiene-styrene, polytetrafluoro-ethylene, polymethacrylate, nylon 6,6, cellulose acetate butyrate, cellulose acetate, rigid vinyl, plasticized vinyl, or polypropylene. In some embodiments, the substrate 102 is made of aluminosilicate glass, borosilicate glass (*e.g.*, Pyrex, Duran, Simax, *etc.*), dichroic glass, germanium / semiconductor glass, glass ceramic, silicate / fused silica glass, soda lime glass, quartz glass, chalcogenide / sulphide glass, fluoride glass, pyrex glass, a glass-based phenolic, cereated glass, or flint glass. In some embodiments, the substrate 102 is a solid cylindrical shape. Such solid cylindrical substrates 102 can be made out of a plastic, glass, metal, or metal alloy.

In some embodiments, the substrate 102 is an electrically conductive nonmetallic material. In some embodiments, the substrate 102 is tubing (*e.g.*, plastic or glass tubing). In some embodiments, the substrate 102 is made of a material such as polybenzamidazole (*e.g.*, CELAZOLE®, available from Boedeker Plastics, Inc., Shiner, Texas). In some embodiments, the substrate 102 is made of polymide (*e.g.*, DuPont™ VESPEL®, or DuPont ™ KAPTON®, Wilmington, Delaware). In some embodiments, the substrate 102 is made of polytetrafluoroethylene (PTFE) or polyetheretherketone (PEEK), each of which is available from Boedeker Plastics, Inc. In some embodiments, the substrate 102 is made of polyamide-imide (*e.g.*, TORLON® PAI, Solvay Advanced Polymers, Alpharetta, Georgia).

In some embodiments, the substrate 102 is made of a glass-based phenolic. Phenolic laminates are made by applying heat and pressure to layers of paper, canvas, linen or glass cloth impregnated with synthetic thermosetting resins. When heat and pressure are applied to the layers, a chemical reaction (polymerization) transforms the separate layers into a single laminated material with a "set" shape that cannot be softened again. Therefore, these materials are called "thermosets." A variety of resin types and cloth materials can be used to manufacture thermoset laminates with a range of mechanical, thermal, and electrical properties. In some embodiments, the substrate 102 is a phenoloic laminate having a NEMA grade of G-3, G-5, G-7, G-9, G-10 or G-11. Exemplary phenolic laminates are available from Boedeker Plastics, Inc.

In some embodiments, the substrate 102 is made of polystyrene. Examples of polystyrene include general purpose polystyrene and high impact polystyrene as detailed in Marks' *Standard Handbook for Mechanical Engineers*, ninth edition, 1987, McGraw-Hill, Inc., p. 6-174, which is hereby incorporated by reference herein in its entirety. In still other embodiments, the substrate 102 is made of cross-linked polystyrene. One example of cross-

linked polystyrene is REXOLITE® (C-Lec Plastics, Inc). Rexolite is a thermoset, in particular, a rigid and translucent plastic produced by cross linking polystyrene with divinylbenzene.

In some embodiments, the substrate 102 is a polyester wire (*e.g.*, a MYLAR® wire). MYLAR® is available from DuPont Teijin Films (Wilmington, Delaware). In still other embodiments, the substrate 102 is made of DURASONE®, which is made by using polyester, vinylester, epoxid and modified epoxy resins combined with glass fibers (Roechling Engineering Plastic Pte Ltd., Singapore).

In still other embodiments, the substrate 102 is made of polycarbonate. Such polycarbonates can have varying amounts of glass fibers (*e.g.*, 10%, 20%, 30%, or 40%) in order to adjust tensile strength, stiffness, compressive strength, as well as the thermal expansion coefficient of the material. Exemplary polycarbonates are ZELUX® M and ZELUX® W, which are available from Boedeker Plastics, Inc.

In some embodiments, the substrate 102 is made of polyethylene. In some embodiments, the substrate 102 is made of low density polyethylene (LDPE), high density polyethylene (HDPE), or ultra high molecular weight polyethylene (UHMW PE). Chemical properties of HDPE are described in Marks' *Standard Handbook for Mechanical Engineers*, ninth edition, 1987, McGraw-Hill, Inc., p. 6-173, which is hereby incorporated by reference herein in its entirety. In some embodiments, the substrate 102 is made of acrylonitrile-butadiene-styrene, polytetrfluoro-ethylene (Teflon), polymethacrylate (lucite or plexiglass), nylon 6,6, cellulose acetate butyrate, cellulose acetate, rigid vinyl, plasticized vinyl, or polypropylene. Chemical properties of these materials are described in Marks' *Standard Handbook for Mechanical Engineers*, ninth edition, 1987, McGraw-Hill, Inc., pp. 6-172 through 1-175, which is hereby incorporated by reference herein in its entirety.

Additional exemplary materials that can be used to form the substrate 102 are found in *Modern Plastics Encyclopedia*, McGraw-Hill; Reinhold Plastics Applications Series, Reinhold Roff, *Fibres, Plastics and Rubbers*, Butterworth; Lee and Neville, *Epoxy Resins*, McGraw-Hill; Bilmetyer, *Textbook of Polymer Science*, Interscience; Schmidt and Marlies, *Principles of high polymer theory and practice*, McGraw-Hill; Beadle (ed.), *Plastics*, Morgan-Grampiand, Ltd., 2 vols. 1970; Tobolsky and Mark (eds.), *Polymer Science and Materials*, Wiley, 1971; Glanville, *The Plastics's Engineer's Data Book,* Industrial Press, 1971; Mohr (editor and senior author), Oleesky, Shook, and Meyers, *SPI Handbook of Technology and Engineering of Reinforced Plastics Composites*, Van Nostrand Reinhold, 1973, each of which is hereby incorporated by reference herein in its entirety. In some embodiments, substrate 102 is polyaniline and polyacetylene doped with arsenic pentafluoride. In some embodiments, conducting material 104 is a filled polymer such as fullerene-filled polymers and/or carbon-black-filled polymers.

Conducting material 104. In Figures 1 and 2, conducting material 104 is depicted as a layer disposed on the underlying substrate 102. In some embodiments, conducting material 104 is a thin layer disposed on all or a portion of the substrate 102. By "a portion of" it is meant at least 20%, or at least 30%, or at least 40%, or at least 50%, or at least 60%, or at least 70%, or at least 80%, or at least 90%, or at least 95% of the underlying substrate 102. In other embodiments, the conducting material 104 and the substrate 102 are, in fact, one and the same. In such embodiments, the substrate 102 is made of a conducting material and there is no layer of conducting material 104 overlayed on the subsrtrate 102. In such embodiments, the substrate is made of any of the materials that can be used to form the conducting material layer 104 in the embodiments that have a conducting material layer 104.

In some embodiments, conducting material 104 is disposed on the substrate 102. Conducting material 104 serves as the first electrode in the assembly. In general, conducting material 104 is made out of any material such that it can support the photovoltaic current generated by the photovoltaic device with negligible resistive losses. In some embodiments, conducting material 104 includes any conductive material, such as aluminum, molybdenum, tungsten, vanadium, rhodium, niobium, chromium, tantalum, titanium, steel, nickel, platinum, silver, gold, an alloy thereof, or any combination thereof. In some embodiments, the conducting material 104 include any conductive material, such as indium tin oxide, titanium nitride, tin oxide, fluorine doped tin oxide, doped zinc oxide, aluminum doped zinc oxide, gallium doped zinc oxide, boron dope zinc oxide indium-zinc oxide, a metal-carbon black-filled oxide, a graphite-carbon black-filled oxide, a carbon black-carbon black-filled oxide, a superconductive carbon black-filled oxide, an epoxy, a conductive glass, or a conductive plastic. As defined herein, a conductive plastic is one that, through compounding techniques, contains conductive fillers which, in turn, impart their conductive properties to the plastic. In some embodiments, the conductive plastics that may be used to form conducting material 104 contain fillers that form sufficient conductive current-carrying paths through the plastic matrix to support the photovoltaic current generated by the photovoltaic device with negligible resistive losses. The plastic matrix of the conductive plastic is typically insulating, but the composite produced exhibits the conductive properties of the filler. In some embodiments, this conductive plastic is inherently conductive without any requirement for a filler. In some embodiments, conducting material 104 is polyaniline and polyacetylene doped with arsenic pentafluoride. In some embodiments, conducting material 104 is a filled polymer such as fullerene-filled polymers and/or carbon-black-filled polymers.

Semiconductor junction 106/108. A semiconductor junction 106/108 is disposed on all or a portion of the conducting material 104. By "a portion of" it is meant at least 20%, or at

least 30%, or at least 40%, or at least 50%, or at least 60%, or at least 70%, or at least 80%, or at least 90%, or at least 95% of the underlying conducting material 104. Semiconductor junction 106/108 is any photovoltaic homojunction, heterojunction, heteroface junction, buried homojunction, a *p-i-n* junction or a tandem junction having an absorber layer that is a direct band-gap absorber (*e.g.*, crystalline silicon) or an indirect band-gap absorber (*e.g.*, amorphous silicon). Such junctions are described in Chapter 1 of Bube, *Photovoltaic Materials*, 1998, Imperial College Press, London, as well as Lugue and Hegedus, 2003, *Handbook of Photovoltaic Science and Engineering*, John Wiley & Sons, Ltd., West Sussex, England, each of which is hereby incorporated by reference herein in its entirety. As such, it is entirely possible for the semiconductor junction 106/108 to have more than just two layers (*e.g.*, layers other than or in addition to an absorber 106 and window layer 108). Details of exemplary types of semiconductors junctions 106/108 in accordance with the present disclosure are disclosed in below. In addition to the exemplary junctions disclosed below, the junctions 106/108 can be multijunctions in which light traverses into the core of the junction 106/108 through multiple junctions that, preferably, have successfully smaller band gaps. In some embodiments, the semiconductor junction 106/108 includes a copper-indium-gallium-diselenide (CIGS) absorber layer.

In some embodiments where a nonplanar substrate 102 is used, the semiconductor junction 106/108 comprises an inner layer and an outer layer where the outer layer comprises a first conductivity type and the inner layer comprises a second, opposite, conductivity type. In an exemplary embodiment, the inner coaxial layer comprises copper-indium-gallium-diselenide (CIGS) whereas the outer coaxial layer comprises In_2Se_3, In_2S_3, ZnS, ZnSe, CdInS, CdZnS, $ZnIn_2Se_4$, $Zn_{1-x}Mg_xO$, CdS, SnO_2, ZnO, ZrO_2, or doped ZnO.

Optional intrinsic layer. Optionally, there is a thin intrinsic layer (*i*-layer) 415 disposed on all or a portion of the semiconductor junction 106/108. By "a portion of" it is meant at least 20%, or at least 30%, or at least 40%, or at least 50%, or at least 60%, or at least 70%, or at least 80%, or at least 90%, or at least 95% of the surface area of the semiconductor junction 106/108. The *i*-layer can be formed using any undoped transparent oxide including, but not limited to, zinc oxide, metal oxide, or any transparent material that is highly insulating. In some embodiments, the *i*-layer is highly pure zinc oxide.

Transparent conductive layer 110. Transparent conductive layer 110 is disposed on all or a portion of the semiconductor junction 106/108 thereby completing the active solar cell circuit. By "a portion of" it is meant at least 20%, or at least 30%, or at least 40%, or at least 50%, or at least 60%, or at least 70%, or at least 80%, or at least 90%, or at least 95% of the surface area of the semiconductor junction layer 410. As noted above, in some embodiments, a

thin *i*-layer is disposed on semiconductor junction 106/108. In such embodiments, the transparent conductive layer 110 is disposed all or a portion of the *i*-layer. By "a portion of" it is meant at least 20%, or at least 30%, or at least 40%, or at least 50%, or at least 60%, or at least 70%, or at least 80%, or at least 90%, or at least 95% of the surface area of the *i*-layer. In some embodiments, the transparent conductive layer 110 is made of tin oxide SnO_x (with or without fluorine doping), indium–tin oxide (ITO), doped zinc oxide (*e.g.*, aluminum doped zinc oxide, gallium doped zinc oxide, boron dope zinc oxide), indium-zinc oxide or any combination thereof. In some embodiments, the transparent conductive layer 110 is either *p*-doped or *n*-doped. In some embodiments, the transparent conductive layer 110 is made of carbon nanotubes. Carbon nanotubes are commercially available, for example, from Eikos (Franklin, Massachusetts) and are described in United States Patent 6,988,925, which is hereby incorporated by reference herein in its entirety. For example, in embodiments where the outer semiconductor layer of junction 106/108is *p*-doped, the transparent conductive layer 110 can be *p*-doped. Likewise, in embodiments where the outer semiconductor layer of semiconductor junction 106/108 is *n*-doped, the transparent conductive layer 110 can be *n*-doped. In general, the transparent conductive layer 110 is preferably made of a material that has very low resistance, suitable optical transmission properties (*e.g.*, greater than 90%), and a deposition temperature that will not damage underlying layers of the semiconductor junction 106/108 and/or the optional *i*-layer. In some embodiments, the transparent conductive layer 110 is an electrically conductive polymer material such as a conductive polytiophene, a conductive polyaniline, a conductive polypyrrole, a PSS-doped PEDOT (*e.g.*, Bayrton), or a derivative of any of the foregoing. In some embodiments, the transparent conductive layer 110 comprises more than one layer, including a first layer comprising tin oxide SnO_x (with or without fluorine doping), indium–tin oxide (ITO), indium-zinc oxide, doped zinc oxide (*e.g.*, aluminum doped zinc oxide, gallium doped zinc oxide, boron dope zinc oxide) or a combination thereof and a second layer comprising a conductive polytiophene, a conductive polyaniline, a conductive polypyrrole, a PSS-doped PEDOT (*e.g.*, BAYRTON), or a derivative of any of the foregoing. Additional suitable materials that can be used to form the transparent conductive layer 110 are disclosed in United States Patent publication 2004/0187917A1 to Pichler, which is hereby incorporated by reference herein in its entirety.

Optional electrode strips. In some embodiments in accordance with the present disclosure, counter-electrode strips or leads are disposed on the transparent conductive layer 110 in order to facilitate electrical current flow. In some embodiments, optional electrode strips are positioned at spaced intervals on the surface of the transparent conductive layer 110. For instance, the electrode strips can run parallel to each other and be spaced out at ninety degree

intervals along the long axis of a nonplanar solar cell device 10. In some embodiments of nonplanar solar cell devices 10, with reference to the cross-section taken through the long axis of the devices, electrode strips are spaced out at up to five degree, up to ten degree, up to fifteen degree, up to twenty degree, up to thirty degree, up to forty degree, up to fifty degree, up to sixty degree, up to ninety degree or up to 180 degree intervals on the surface of the transparent conductive layer 110. In some embodiments, there is a single electrode strip on the surface of the transparent conductive layer 110. In many embodiments, there is no electrode strip on the surface of the transparent conductive layer 110. In some embodiments, there is two, three, four, five, six, seven, eight, nine, ten, eleven, twelve, fifteen or more, or thirty or more electrode strips on the transparent conductive layer 110, all running parallel, or near parallel, to each down the long axis of the photovoltaic device 10. In some embodiments wherein the photovoltaic device 10 is cylindrical, electrode strips are evenly spaced about the circumference of the transparent conductive layer 110. In alternative embodiments, electrode strips are not evenly spaced about the circumference of the transparent conductive layer 110. In some embodiments, the electrode strips are only on one face of the photovoltaic device 10. In some embodiments, the electrode strips are made of conductive epoxy, conductive ink, copper or an alloy thereof, aluminum or an alloy thereof, nickel or an alloy thereof, silver or an alloy thereof, gold or an alloy thereof, a conductive glue, or a conductive plastic.

In some embodiments, the electrode strips are interconnected to each other by grid lines. These grid lines can be thicker than, thinner than, or the same thickness as the electrode strips. These grid lines can be made of the same or different electrically material as the electrode strips.

In some embodiments, the electrode strips are deposited on the transparent conductive layer using ink jet printing. Examples of conductive ink that can be used for such strips include, but are not limited to silver loaded or nickel loaded conductive ink. In some embodiments, epoxies as well as anisotropic conductive adhesives can be used to construct electrode strips. In typical embodiments, such inks or epoxies are thermally cured in order to form the electrode strips.

Filler layer 330. Advantageously, the current solar cell devices 10 employ a gel, resin, non-solid, or otherwise highly viscous matter for layer 330. Filler layer can be, for example, a gel or liquid. The material is added to the assembly as a liquid, and allowed to cure to the gel or other viscous non-solid state. However, in this approach, the formed material has a much higher coefficient of expansion than conventional materials such as ethylene-vinyl acetate. Thus, during a typical thermal cycle, one can expect substantial volume changes in layer 330 relative to the use of conventional material for layer 330 such as EVA.

In one example, a medium viscosity polydimethylsiloxane mixed with an elastomer-type dielectric gel can be used to make the filler layer 330. In one case, as an example, a mixture of 85% (by weight) Dow Corning 200 fluid, 50 centistoke viscosity (PDMS, polydimethylsiloxane); 7.5 % Dow Corning 3-4207 Dielectric Tough Gel, Part A –Resin 7.5 % Dow Corning 3-4207 Dielectric Tough Gel, Part B – Pt Catalyst, is used to make the filler layer 330. Of course, other oils, gels, or silicones can be used for the filler layer 300, and accordingly this specification should be read to include those other oils, gels and silicones to generate the described layer for the filler layer 330. Such oils include silicon based oils, and the gels include many commercially available dielectric gels, to name a few. Curing of silicones can also extend beyond a gel like state. Of course, commercially available dielectric gels and silicones and the various formulations are contemplated as being usable in this application.

In some embodiments, a silicone-based dielectric gel can be used *in situ*. Or, as indicated above, the dielectric gel can be mixed with a silicone based oil to reduce both beginning and ending viscosities. The ratio of silicone oil by weight in the mixture can be varied. As mentioned before, the ratio of silicone oil by weight in the mixture of silicone-based oil and silicone-based dielectric gel in the specific example above is 85%. However, ratios at or about (*e.g.* +- 2%) 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%, and 85% are all contemplated. Ranges of 20%-30%, 25%-35%, 30%-40%, 35%-45%, 40%-50%, 45%-55%, 50%-60%, 55%-65%, 60%-70%, 65%-75%, 70%-80%, 75%-85%, and 80%-90% (by weight) are also contemplated. Further, these same ratios by weight can be contemplated for the mixture when using other types of oils or acrylates to lessen the beginning viscosity of the gel mixture alone.

Transparent casing 310. The transparent casing 310 seals the photovoltaic device as illustrated in Figure 2. In some embodiments the transparent casing 310 is made of plastic or glass. In some embodiments, the transparent casing 310 is made of a urethane polymer, an acrylic polymer, polymethylmethacrylate (PMMA), a fluoropolymer, silicone, poly-dimethyl siloxane (PDMS), silicone gel, epoxy, ethyl vinyl acetate (EVA), perfluoroalkoxy fluorocarbon (PFA), nylon / polyamide, cross-linked polyethylene (PEX), polyolefin, polypropylene (PP), polyethylene terephtalate glycol (PETG), polytetrafluoroethylene (PTFE), thermoplastic copolymer (for example, ETFE®, which is a derived from the polymerization of ethylene and tetrafluoroethylene: TEFLON® monomers), polyurethane / urethane, polyvinyl chloride (PVC), polyvinylidene fluoride (PVDF), TYGON®, vinyl, VITON®, or any combination or variation thereof.

In some embodiments, the transparent casing 310 comprises a plurality of transparent casing layers. In some embodiments, each transparent casing layer is composed of a different

material. For example, in some embodiments, the transparent casing 310 comprises a first transparent casing layer and a second transparent casing layer. Depending on the exact configuration of the photovoltaic device 10, the first transparent casing layer is disposed on the transparent conductive layer 110, optional filler layer 330 or a water resistance layer. The second transparent casing layer is then disposed on the first transparent casing layer.

In some embodiments, each transparent casing layer has different properties. In one example, the outer transparent casing layer has excellent UV shielding properties whereas the inner transparent casing layer has good water proofing characteristics. Moreover, the use of multiple transparent casing layers can be used to reduce costs and/or improve the overall properties of the transparent casing 310. For example, one transparent casing layer may be made of an expensive material that has a desired physical property. By using one or more additional transparent casing layers, the thickness of the expensive transparent casing layer may be reduced, thereby achieving a savings in material costs. In another example, one transparent casing layer may have excellent optical properties (*e.g.*, index of refraction, *etc.*) but be very heavy. By using one or more additional transparent casing layers, the thickness of the heavy transparent casing layer may be reduced, thereby reducing the overall weight of transparent casing 310.

In some embodiments, the transparent casing 310 is made of glass. Any of a wide variety of glasses can be used to make the transparent casing 310, some of which are described here. In some embodiments, the transparent casing 310 is made of silicon dioxide (SiO_2) glass In some embodiments, the transparent casing 310 is made of soda lime glass formed from silicon dioxide, soda (*e.g.*, sodium carbonate Na_2CO_3), or potash, a potassium compound, and lime (calcium oxide, CaO). In some embodiments, the transparent casing 310 is made of lead glass, such as lead crystal or flint glass. In some embodiments, silicon dioxide glass doped with boron, barium, thorium oxide, lanthanum oxide, iron , or cerium(IV) oxide is used to make transparent casing 310. In some embodiments, transparent casing 310 is made of aluminosilicate, borosilicate (*e.g.*, PYREX®, DURAN®, SIMAX®), dichroic, germanium / semiconductor, glass ceramic, silicate / fused silica, soda lime, quartz, chalcogenide / sulphide, or cereated glass.

In some embodiments, transparent casing 310 is made of clear plastic such as ethyl vinyl acetate (EVA), perfluoroalkoxy fluorocarbon (PFA), nylon / polyamide, cross-linked polyethylene (PEX), polyolefin, polypropylene (PP), polyethylene terephtalate glycol (PETG), polytetrafluoroethylene (PTFE), thermoplastic copolymer (for example, ETFE®), polyurethane / urethane, polyvinyl chloride (PVC), polyvinylidene fluoride (PVDF), TYGON®, Vinyl, or VITON®.

Optional water resistant layer. In some embodiments, one or more layers of water resistant layer are coated over the photovoltaic device 10 to prevent the damaging effects of water. In some embodiments, this water resistant layer is coated onto the transparent conductive layer 110 prior to depositing filler layer 330 and encasing the photovoltaic device 10 in the transparent casing 310. In some embodiments, such water resistant layers are circumferentially coated onto the transparent casing 310 itself. The optical properties of the water resistant layer are chosen so that they do not interfere with the absorption of incident solar radiation by the photovoltaic device 10. In some embodiments, this water resistant layer is made of clear silicone, SiN, SiO_xN_y, SiO_x, or Al_2O_3, where x and y are integers. In some embodiments, the optional water resistant layer is made of a Q-type silicone, a silsequioxane, a D-type silicon, or an M-type silicon.

Optional antireflective coating. In some embodiments, an optional antireflective coating is also disposed on the photovoltaic device 10 (*e.g.*, on the transparent casing 310) to maximize solar cell efficiency. In some embodiments, there is a both a water resistant layer and an antireflective coating deposited on the transparent casing 310. In some embodiments, a single layer serves the dual purpose of a water resistant layer and an anti-reflective coating. In some embodiments, the antireflective coating is made of MgF_2, silicone nitrate, titanium nitrate, silicon monoxide (SiO), or silicon oxide nitrite. In some embodiments, there is more than one layer of antireflective coating. In some embodiments, there is more than one layer of antireflective coating and each layer is made of the same material. In some embodiments, there is more than one layer of antireflective coating and each layer is made of a different material.

In some embodiments, some of the layers of multi-layered photovoltaic devices 10 are constructed using cylindrical magnetron sputtering techniques. In some embodiments, some of the layers of multi-layered photovoltaic devices 10 are constructed using conventional sputtering methods or reactive sputtering methods on long tubes or strips. Sputtering coating methods for nonplanar substrates 102 such as long tubes and strips are disclosed in for example, Hoshi *et al.*, 1983, "Thin Film Coating Techniques on Wires and Inner Walls of Small Tubes via Cylindrical Magnetron Sputtering," *Electrical Engineering in Japan* 103:73-80; Lincoln and Blickensderfer, 1980, "Adapting Conventional Sputtering Equipment for Coating Long Tubes and Strips," *J. Vac. Sci. Technol.* 17:1252-1253; Harding, 1977, "Improvements in a dc Reactive Sputtering System for Coating Tubes," *J. Vac. Sci. Technol.* 14:1313-1315; Pearce, 1970, "A Thick Film Vacuum Deposition System for Microwave Tube Component Coating," *Conference Records of 1970 Conference on Electron Device Techniques* 208-211; and Harding *et al.*, 1979, "Production of Properties of Selective Surfaces Coated onto Glass Tubes by a Magnetron Sputtering System," *Proceedings of the International Solar Energy Society* 1912-

1916, each of which is hereby incorporated by reference herein in its entirety.

Optional fluorescent material. In some embodiments, a fluorescent material (*e.g.*, luminescent material, phosphorescent material) is coated on a surface of a layer of the photovoltaic device 10. In some embodiments, the fluorescent material is coated on the luminal surface and/or the exterior surface of transparent casing 310. In some embodiments, the fluorescent material is coated on the outside surface of the transparent conducting material 110. In some embodiments, the photovoltaic device includes a water resistant layer and the fluorescent material is coated on the water resistant layer. In some embodiments, more than one surface of the photovoltaic device 10 is coated with optional fluorescent material. In some embodiments, the fluorescent material absorbs blue and/or ultraviolet light, which some semiconductor junctions 106/108 do not use to convert to electricity, and the fluorescent material emits light in visible and/or infrared light which is useful for electrical generation in some semiconductor junctions 106/108.

Fluorescent, luminescent, or phosphorescent materials can absorb light in the blue or UV range and emit visible light. Phosphorescent materials, or phosphors, usually comprise a suitable host material and an activator material. The host materials are typically oxides, sulfides, selenides, halides or silicates of zinc, cadmium, manganese, aluminum, silicon, or various rare earth metals. The activators are added to prolong the emission time.

In some embodiments, phosphorescent materials are incorporated in the systems and methods of the present disclosure to enhance light absorption by the photovoltaic device 10. In some embodiments, the phosphorescent material is directly added to the material used to make the transparent casing 310. In some embodiments, the phosphorescent materials are mixed with a binder for use as transparent paints to coat various outer or inner layers of the photovoltaic device 10, as described above.

Exemplary phosphors include, but are not limited to, copper-activated zinc sulfide (ZnS:Cu) and silver-activated zinc sulfide (ZnS:Ag). Other exemplary phosphorescent materials include, but are not limited to, zinc sulfide and cadmium sulfide (ZnS:CdS), strontium aluminate activated by europium ($SrAlO_3$:Eu), strontium titanium activated by praseodymium and aluminum (SrTiO3:Pr, Al), calcium sulfide with strontium sulfide with bismuth ((Ca,Sr)S:Bi), copper and magnesium activated zinc sulfide (ZnS:Cu,Mg), or any combination thereof.

Methods for creating phosphor materials are known in the art. For example, methods of making ZnS:Cu or other related phosphorescent materials are described in United States Patent Nos. 2,807,587 to Butler *et al.*; 3,031,415 to Morrison *et al.*; 3,031,416 to Morrison *et al.*; 3,152,995 to Strock; 3,154,712 to Payne; 3,222,214 to Lagos *et al.*; 3,657,142 to Poss;

4,859,361 to Reilly *et al.*, and 5,269,966 to Karam *et al.*, each of which is hereby incorporated by reference herein in its entirety. Methods for making ZnS:Ag or related phosphorescent materials are described in United States Patent Nos. 6,200,497 to Park *et al.*, 6,025,675 to Ihara *et al.*; 4,804,882 to Takahara *et al.*, and 4,512,912 to Matsuda *et al.*, each of which is hereby incorporated by reference herein in its entirety. Generally, the persistence of the phosphor increases as the wavelength decreases. In some embodiments, quantum dots of CdSe or similar phosphorescent material can be used to get the same effects. See Dabbousi *et al.*, 1995, "Electroluminescence from CdSe quantum-dot/polymer composites," Applied Physics Letters 66 (11): 1316-1318; Dabbousi *et al.*, 1997 "(CdSe)ZnS Core-Shell Quantum Dots: Synthesis and Characterization of a Size Series of Highly Luminescent Nanocrystallites," J. Phys. Chem. B, 101: 9463-9475; Ebenstein *et al.*, 2002, "Fluorescence quantum yield of CdSe:ZnS nanocrystals investigated by correlated atomic-force and single-particle fluorescence microscopy," Applied Physics Letters 80: 1023-1025; and Peng *et al.*, 2000, "Shape control of CdSe nanocrystals," Nature 104: 59-61; each of which is hereby incorporated by reference herein in its entirety.

In some embodiments, optical brighteners are used in the optional fluorescent layers of the present disclosure. Optical brighteners (also known as optical brightening agents, fluorescent brightening agents or fluorescent whitening agents) are dyes that absorb light in the ultraviolet and violet region of the electromagnetic spectrum, and re-emit light in the blue region. Such compounds include stilbenes (*e.g.*, trans-1, 2-diphenylethylene or (E)-1, 2-diphenylethene). Another exemplary optical brightener that can be used in the optional fluorescent layers of the present disclosure is umbelliferone (7-hydroxycoumarin), which also absorbs energy in the UV portion of the spectrum. This energy is then re-emitted in the blue portion of the visible spectrum. More information on optical brighteners is in Dean, 1963, *Naturally Occurring Oxygen Ring Compounds*, Butterworths, London; Joule and Mills, 2000, *Heterocyclic Chemistry*, 4th edition, Blackwell Science, Oxford, United Kingdom; and Barton, 1999, *Comprehensive Natural Products Chemistry* 2: 677, Nakanishi and Meth-Cohn eds., Elsevier, Oxford, United Kingdom, 1999.

Circumferentially disposed. In some instances, the above-disclosed materials are successively circumferentially disposed on a nonplanar (*e.g.*, cylindrical) substrate 102 in order to form a solar cell 12 of a photovoltaic device 10. As used herein, the term circumferentially disposed is not intended to imply that each such layer of material is necessarily deposited on an underlying layer. In fact, such layers could be molded or otherwise formed on an underlying layer. Nevertheless, the term circumferentially disposed means that an overlying layer is disposed on an underlying layer such that there is no annular space between the overlying layer

and the underlying layer. Furthermore, as used herein, the term circumferentially disposed means that an overlying layer is disposed on at least fifty percent of the perimeter of the underlying layer. Furthermore, as used herein, the term circumferentially disposed means that an overlying layer is disposed along at least half of the length of the underlying layer.

Circumferentially sealed. As used herein, the term circumferentially sealed is not intended to imply that an overlying layer or structure is necessarily deposited on an underlying layer or structure. In fact, such layers or structures (*e.g.*, transparent casing 310) can be molded or otherwise formed on an underlying layer or structure. Nevertheless, the term circumferentially sealed means that an overlying layer or structure is disposed on an underlying layer or structure such that there is no annular space between the overlying layer or structure and the underlying layer or structure. Furthermore, as used herein, the term circumferentially sealed means that an overlying layer is disposed on the full perimeter of the underlying layer. In typical embodiments, a layer or structure circumferentially seals an underlying layer or structure when it is circumferentially disposed around the full perimeter of the underlying layer or structure and along the full length of the underlying layer or structure. However, it is possible for a circumferentially sealing layer or structure does not extend along the full length of an underlying layer or structure.

Rigid. In some embodiments, the substrate 102 and/or the transparent casing 310 is rigid. Rigidity of a material can be measured using several different metrics including, but not limited to, Young's modulus. In solid mechanics, Young's Modulus (E) (also known as the Young Modulus, modulus of elasticity, elastic modulus or tensile modulus) is a measure of the stiffness of a given material. It is defined as the ratio, for small strains, of the rate of change of stress with strain. This can be experimentally determined from the slope of a stress-strain curve created during tensile tests conducted on a sample of the material. Young's modulus for various materials is given in the following table.

Material	**Young's modulus (E) in GPa**	**Young's modulus (E) in lbf/in² (psi)**
Rubber (small strain)	0.01-0.1	1,500-15,000
Low density polyethylene	0.2	30,000
Polypropylene	1.5-2	217,000-290,000
Polyethylene terephthalate	2-2.5	290,000-360,000
Polystyrene	3-3.5	435,000-505,000
Nylon	3-7	290,000-580,000
Aluminum alloy	69	10,000,000
Glass (all types)	72	10,400,000
Brass and bronze	103-124	17,000,000

Material	Young's modulus (E) in GPa	Young's modulus (E) in lbf/in² (psi)
Titanium (Ti)	105-120	15,000,000-17,500,000
Carbon fiber reinforced plastic (unidirectional, along grain)	150	21,800,000
Wrought iron and steel	190-210	30,000,000
Tungsten (W)	400-410	58,000,000-59,500,000
Silicon carbide (SiC)	450	65,000,000
Tungsten carbide (WC)	450-650	65,000,000-94,000,000
Single Carbon nanotube	1,000+	145,000,000
Diamond (C)	1,050-1,200	150,000,000-175,000,000

In some embodiments of the present application, a material (*e.g.*, the substrate 102, the transparent casing 310, *etc.*) is deemed to be rigid when it is made of a material that has a Young's modulus of 20 GPa or greater, 30 GPa or greater, 40 GPa or greater, 50 GPa or greater, 60 GPa or greater, or 70 GPa or greater. In some embodiments a material (*e.g.*, the substrate 102, the transparent casing 310, *etc.*) is deemed to be rigid when the Young's modulus for the material is a constant over a range of strains. Such materials are called linear, and are said to obey Hooke's law. Thus, in some embodiments, the substrate 102 is made out of a linear material that obeys Hooke's law. Examples of linear materials include, but are not limited to, steel, carbon fiber, and glass. Rubber and soil (except at very low strains) are non-linear materials. In some embodiments, a material is considered rigid when it adheres to the small deformation theory of elasticity, when subjected to any amount of force in a large range of forces (e.g., between 1 dyne and 10^5 dynes, between 1000 dynes and 10^6 dynes, between 10,000 dynes and 10^7 dynes), such that the material only undergoes small elongations or shortenings or other deformations when subject to such force. The requirement that the deformations (or gradients of deformations) of such exemplary materials are small means, mathematically, that the square of either of these quantities is negligibly small when compared to the first power of the quantities when exposed to such a force. Another way of stating the requirement for a rigid material is that such a material does not visibly deform over a large range of forces (*e.g.*, between 1 dyne and 10^5 dynes, between 1000 dynes and 10^6 dynes, between 10,000 dynes and 10^7 dynes), is well characterized by a strain tensor that only has linear terms. The strain tensor for materials is described in Borg, 1962, *Fundamentals of Engineering Elasticity*, Princeton, New Jersey, pp. 36-41, which is hereby incorporated by reference herein in its entirety. In some embodiments, a material is considered rigid when a sample of the material of sufficient size and dimensions does not bend under the force of gravity.

In general, the extent to which a body (*e.g.*, the substrate 102, the transparent casing 310, *etc.*) deflects under a force, *e.g.*, the stiffness of the body, is related to the Young's Modulus of the material from which it is made, the body's length and cross-sectional dimensions, and the force applied to the body, as is known to those of ordinary skill in the art. In some embodiments, the Young's Modulus of the body material, and the body's length and cross-sectional area, are selected such that the body (*e.g.*, the substrate 401, casing 310, *etc.*) substantially does not visibly deflect (bend) when a first end of the body is subjected to a force of, *e.g.*, between 1 dyne and 10^5 dynes, between 100 dynes and 10^6 dynes, or between 10,000 dynes and 10^7 dynes, while a second end of the body is held fixed. In some embodiments, the Young's Modulus of the body material, and the body's length and cross-sectional area, are selected such that the body (*e.g.*, the substrate 401, casing 310, etc.) substantially does not visibly deflect when a first end of the body is subjected to the force of gravity, while a second end of the body is held fixed.

Non-planar. The present application is not limited to elongated photovoltaic modules and substrates that have rigid cylindrical shapes or are solid rods. In some embodiments, all or a portion of the substrate 102 can be characterized by a cross-section bounded by any one of a number of shapes other than the circular shape. The bounding shape can be any one of circular, ovoid, or any shape characterized by one or more smooth curved surfaces, or any splice of smooth curved surfaces. The bounding shape can be an n-gon, where n is 3, 5, or greater than 5. The bounding shape can also be linear in nature, including triangular, rectangular, pentangular, hexagonal, or having any number of linear segmented surfaces. Or, the cross-section can be bounded by any combination of linear surfaces, arcuate surfaces, or curved surfaces.

In some embodiments, a first portion of the substrate 102 is characterized by a first cross-sectional shape and a second portion of the substrate 102 is characterized by a second cross-sectional shape, where the first and second cross-sectional shapes are the same or different. In some embodiments, at least zero percent, at least ten percent, at least twenty percent, at least thirty percent, at least forty percent, at least fifty percent, at least sixty percent, at least seventy percent, at least eighty percent, at least ninety percent or all of the length of the substrate 102 is characterized by the first cross-sectional shape. In some embodiments, the first cross-sectional shape is planar (*e.g.*, has no arcuate side) and the second cross-sectional shape has at least one arcuate side.

Elongated. For purposes of defining the term "elongated" an object (*e.g.*, substrate, elongated photovoltaic module, *etc.*) is considered to have a width dimension (short dimension,

for example diameter of a cylindrical object) and a longitudinal (long) dimension. In some embodiments is deemed elongated when the longitudinal dimension of the object is at least four times greater than the width dimension. In other embodiments, an object is deemed to be elongated when the longitudinal dimension of the object is at least five times greater than the width dimension. In yet other embodiments, an object is deemed to be elongated when the longitudinal dimension of the object is at least six times greater than the width dimension of the object. In some embodiments, an object is deemed to be elongated when the longitudinal dimension of the object is 100 cm or greater and a cross section of the object includes at least one arcuate edge. In some embodiments, an object is deemed to be elongated when the longitudinal dimension of the object is 100 cm or greater and the object has a cylindrical shape. In some embodiments, the photovoltaic modules are elongated. In some embodiments, the substrates are elongated.

1.3 EXEMPLARY SEMICONDUCTOR JUNCTIONS

Referring to Figure 10A, in one embodiment, semiconductor junction 106/108 is a heterojunction between an absorber layer 106, disposed on all or a portion of the conducting material 104, and a junction partner layer 108, disposed on all or a portion of the absorber layer 106. In other embodiments, junction partner layer 108 is disposed on all or a portion of back-electrode 104, and absorber layer 106 is disposed on all or a portion of junction partner layer 108. Layers 106 and 108 are composed of different semiconductors with different band gaps and electron affinities such that the junction partner layer 108 has a larger band gap than the absorber layer 106.

For example, in some embodiments, the absorber layer 106 is *p*-doped and the junction partner layer 108 is *n*-doped. In such embodiments, the transparent conducting layer 110 is n^+-doped. In alternative embodiments, the absorber layer 106 is *n*-doped and the junction partner layer 108 is *p*-doped. In such embodiments, the transparent conductive layer 110 is p^+-doped. In some embodiments, any of the semiconductors listed in Pandey, *Handbook of Semiconductor Electrodeposition*, Marcel Dekker Inc., 1996, Appendix 5, which is hereby incorporated by reference herein in its entirety, are used to form semiconductor junction 106/108.

Characteristics of solar cells based on p-n junctions. The principles of operation of solar cells based on p-n junctions (which is one form of semiconductor junction 106/108) are well understood. Briefly, a p-type semiconductor is placed in intimate contact with an n-type semiconductor. At equilibrium, electrons diffuse from the n-type side of the junction to the p-type side of the junction, where they recombine with holes, and holes diffuse from the p-type

side of the junction to the n-type side of the junction, where they recombine with electrons. The resultant imbalance of charges creates a potential difference across the junction and forms a "space charge region" or "depletion layer," which no longer contains mobile charge carriers, near the junction.

The p-type and n-type sides of the junction are connected to respective electrodes that are connected to an external load. In operation, one of the two junction layers behaves as an absorber, and the other junction layer is referred to as a "junction partner layer." The absorber absorbs photons having energies above the band gap of the material of which it is made (more below), which generates electrons that drift under the influence of the potential generated by the junction. "Drift" is a charged particle's response to an applied electric field. The electrons drift to the electrode connected to the absorber, drift through the external load (thus generating electricity), and then into the junction partner layer. At the junction partner layer, the electrons recombine with holes in the junction partner layer. In some junctions 106/108 of the present application, a significant portion if not substantially all of the electricity generated by the junction (e.g., the electrons in the external load) derives from the absorption of photons by the absorber, *e.g.*, greater than 30%, greater than 50%, greater than 60%, greater than 70%, greater than 80%, greater than 90%, greater than 95%, greater than 98%, greater than 99%, or substantially all of the electricity generated by the junction 106/108 derives from the absorption of photons by the absorber. In some junctions 106/108 of the present application, a significant portion if not substantially all of the electricity generated by a solar cell 12 in the photovoltaic device 10 (*e.g.*, the electrons in the external load) derives from the absorption of photons by the absorber, *e.g.*, greater than 30%, greater than 50%, greater than 60%, greater than 70%, greater than 80%, greater than 90%, greater than 95%, greater than 98%, greater than 99%, or substantially all of the electricity generated by the solar cell 12 in the photovoltaic device 10 derives from the absorption of photons by the absorber. For further details, see Chapter 3 of *Handbook of Photovoltaic Science and Engineering*, 2003, Luque and Hegedus (eds.), Wiley & Sons, West Sussex, England, the entire contents of which are hereby incorporated by reference herein.

Note that dye and polymer-based thin-film solar cells are generally not p-n-junction solar cells, and the dominant mode of electron-hole separation is via charge carrier diffusion, not drift in response to an applied electric field. For further details on dye- and polymer-based thin film solar cells, see Chapter 15 of *Handbook of Photovoltaic Science and Engineering*, 2003, Luque and Hegedus (eds.), Wiley & Sons, West Sussex, England, the entire contents of which are hereby incorporated by reference herein.

Material Characteristics. In some embodiments, materials for use in the semiconductor

junctions 106/108 are inorganic meaning that they substantially do not contain reduced carbon, noting that negligible amounts of reduced carbon may naturally exist as impurities in such materials. As used herein, the term "inorganic compound" refers to all compounds, except hydrocarbons and derivatives of hydrocarbons as set forth by Moeller, 1982, *Inorganic Chemistry, A modern Introduction,* Wiley, New York, p. 2, which is hereby incorporated by reference.

In some embodiments, materials for use in semiconductor junctions are solids, that is, the atoms making up the material have fixed positions in space relative to each other, with the exception that the atoms may vibrate about those positions due to the thermal energy in the material. A solid object is in the state of matter characterized by resistance to deformation and changes of volume. At the microscopic scale, a solid has the following properties. First, the atoms or molecules that make up a solid are packed closely together. Second, the constituent elements of a solid have fixed positions in space relative to each other. This accounts for the solid's rigidity. A crystal structure, which is one non-limiting form of a solid, is a unique arrangement of atoms in a crystal. A crystal structure is composed of a unit cell, a set of atoms arranged in a particular way; which is periodically repeated in three dimensions on a lattice. The spacing between unit cells in various directions is called its lattice parameters. The symmetry properties of the crystal are embodied in its space group. A crystal's structure and symmetry play a role in determining many of its properties, such as cleavage, electronic band structure, and optical properties. Third, if sufficient force is applied, either of the first and second properties identified above can be disrupted, causing permanent deformation.

In some embodiments, the semiconductor junction 106/108 is in a solid state. In some embodiments, any combination of the substrate 102, the back-electrode 404, the semiconductor junction 106/108, the optional intrinsic layer 415, the transparent conductive layer 110, the transparent casing 310, and the water resistant layer is in the solid state.

Many, but not all, of the described semiconductor materials are crystalline, or polycrystalline. By "crystalline" it is meant that the atoms or molecules making up the material are arranged in an ordered, repeating pattern that extends in all three spatial dimensions. By "polycrystalline" it is meant that the material includes crystalline regions, but that the arrangement of atoms or molecules within each particular crystalline region is not necessarily related to the arrangement of atoms or molecules within other crystalline regions. In polycrystalline materials, grain boundaries typically separate one crystalline region from another. In some embodiments, more than 10%, more than 20%, more than 30%, more than 40%, more than 50%, more than 60%, more than 70%, more than 80%, more than 90%, more than 99% or more of the material making up the absorber and/or the junction partner layer is in

a crystalline state. In other words, in some embodiments more than 10%, more than 20%, more than 30%, more than 40%, more than 50%, more than 60%, more than 70%, more than 80%, more than 90%, more than 99% or more of the molecules of the material making up the absorber and/or the junction partner layer of a semiconductor junction 106/108 are independently arranged into one or more crystals, where such crystals are in the triclinic, monoclinic, orthorhombic, tetragonal, trigonal (rhombohedral lattice), trigonal (hexagonal lattice), hexagonal, or cubic crystal system defined by Table 3.1 of Stout and Jensen, 1989, *X-ray Structure Determination, A Practical Guide*, John Wiley & Sons, p. 42, which is hereby incorporated by reference herein. In some embodiments, more than 10%, more than 20%, more than 30%, more than 40%, more than 50%, more than 60%, more than 70%, more than 80%, more than 90%, more than 99% or more of the molecules of the material making up the absorber and/or the junction partner layer of a semiconductor junction 106/108 are independently arranged into one or more crystals that each conform to the symmetry of the triclinic crystal system, that each conform to the symmetry of the monoclinic crystal system, that each conform to the symmetry of the orthorhombic crystal system, that each conform to the symmetry of the tetragonal crystal system, that each conform to the symmetry of the trigonal (rhombohedral lattice) crystal system, that each conform to the symmetry of the trigonal (hexagonal lattice) crystal system, that that each conform to the symmetry of the hexagonal crystal system, or that each conform to the symmetry of the cubic crystal system. In some embodiments, more than 10%, more than 20%, more than 30%, more than 40%, more than 50%, more than 60%, more than 70%, more than 80%, more than 90%, more than 99% or more of the molecules of the material making up the absorber and/or the junction partner layer of a semiconductor junction 410 are independently arranged into one or more crystals, where each of the one or more crystals is independently in any one of the 230 possible space groups. For a list of the 230 possible space groups, see Table 3.4 of Stout and Jensen, 1989, *X-ray Structure Determination, A Practical Guide*, John Wiley & Sons, p. 68-69, which is hereby incorporated by reference herein. In some embodiments, more than 10%, more than 20%, more than 30%, more than 40%, more than 50%, more than 60%, more than 70%, more than 80%, more than 90%, more than 99% or more of the molecules of the material making up the absorber and/or the junction partner layer of a semiconductor junction 106/108 are arranged in a cubic space group. For a list of each of the cubic space groups, see Table 3.4 of Stout and Jensen, 1989, *X-ray Structure Determination, A Practical Guide*, John Wiley & Sons, p. 68-69, which is hereby incorporated by reference herein. In some embodiments, more than 10%, more than 20%, more than 30%, more than 40%, more than 50%, more than 60%, more than 70%, more than 80%, more than 90%, more than 99% or more of the molecules of the material making up

the absorber and/or the junction partner layer of a semiconductor junction 106/108 are arranged in a tetragonal space group. For a list of each of the tetragonal space groups, see Table 3.4 of Stout and Jensen, 1989, *X-ray Structure Determination, A Practical Guide*, John Wiley & Sons, p. 68-69, which is hereby incorporated by reference herein. In some embodiments, more than 10%, more than 20%, more than 30%, more than 40%, more than 50%, more than 60%, more than 70%, more than 80%, more than 90%, more than 99% or more of the molecules of the material making up the absorber and/or the junction partner layer of a semiconductor junction 410 are arranged in the Fm3m space group. The absorber and/or the junction partner layer of a semiconductor junction 106/108 may include one or more grain boundaries.

In typical embodiments, the materials used in semiconductor junctions 106/108 are solid inorganic semiconductors. That is, such materials are inorganic, they are in a solid state, and they are semiconductors. A direct consequence of such materials being in such a state is that the electronic band structure of such materials has a unique band structure in which there is an almost fully occupied valence band and an almost fully unoccupied conduction band, with a forbidden gap between the valence band and the conduction band that is referred to herein as the band gap. In some embodiments, at least 80%, or at least 90%, or substantially of the molecules in the absorber layer are inorganic semiconductor molecules, and at least 80%, or at least 90%, or substantially all of the molecules in the junction partner layer are inorganic semiconductor molecules.

Others of the described semiconductor materials, such as Si in some embodiments, are amorphous. By "amorphous" it is meant a material in which there is no long-range order of the positions of the atoms or molecules making up the material. For example, on length scales greater than 10 nm, or greater than 50 nm, there is typically no recognizable order in an amorphous material. However, on small length scales (*e.g.*, less than 5 nm, or less than 2 nm) even amorphous materials may have some short-range order among the atomic positions such that, on small length scales, such materials obey the requirements of one of the 230 possible space groups in standard orientation.

In some embodiments, semiconducting materials suitable for use in various embodiments of solar cells, such as those described herein, are non-polymeric (e.g., not based on organic polymers). In general, although a polymer may have a repeating chemical structure based on the monomeric units of which it is made, those of skill in the art recognize that polymers are typically found in the amorphous state because there is typically no long-range order to the spatial positions of portions of the polymer relative to other portions and because the spatial positions of such polymers do not obey the symmetry requirements of any of the 230 possible space groups or any of the symmetry requirements of any of the seven crystal systems.

However, it is recognized that polymer materials may have short-range crystalline regions.

Band gaps. In some embodiments of the present application, at least forty percent, at least fifty percent, at least sixty percent, at least seventy percent, at least eighty percent, at least ninety percent, at least ninety-five percent, at least 99 percent or substantially all of the energy generated in the solar cell is generated by the absorber layer in a semiconductor junction 106/108 absorbing photons with energies at or above the band gap of the absorber layer. For example, at least about 30%, at least about 40%, at least about 50%, at least about 60%, at least about 70%, at least about 80%, at least about 85%, at least about 90%, at least about 95%, at least about 98%, at least about 99%, or even more of the energy generated in the solar cell is generated by the absorber layer absorbing photons with energies at or above the band gap of the absorber layer.

Usefully, in many embodiments, the absorber layer and the junction partner layer each have a band gap between, *e.g.*, about 0.6 eV (about 2066 nm) and about 2.4 eV (about 516 nm). In some embodiments, a junction partner layer has a band gap between, *e.g.*, about 0.7 eV (about 1771 nm) and about 2.2 eV (about 563 nm). In some embodiments, the absorber layer or the junction partner layer in a semiconductor junction 106/108 has a band gap between, *e.g.*, about 0.8 eV (about 1550 nm) and about 2.0 eV (about 620 nm). In some embodiments, an absorber layer or a junction partner layer in a semiconductor junction 106/108 has a band gap between, *e.g.*, about 0.9 eV (about 1378 nm) and about 1.8 eV (about 689 nm). In some embodiments, an absorber layer or a junction partner layer in a semiconductor junction 106/108 has a band gap between, *e.g.*, about 1 eV (about 1240 nm) and about 1.6 eV (about 775 nm). In some embodiments, an absorber layer or a junction partner layer in a semiconductor junction 106/108 has a band gap between, *e.g.*, about 1.1 eV (about 1127 nm) and about 1.4 eV (about 886 nm). In some embodiments, an absorber layer or a junction partner layer in a semiconductor junction 106/108 has a band gap between, *e.g.*, about 1.1 eV (about 1127 nm) and about 1.2 eV (about 1033 nm). In some embodiments, an absorber layer or a junction partner layer in a semiconductor junction 106/108 has a band gap between, *e.g.*, about 1.2 eV (about 1033 nm) and about 1.3 eV (about 954 nm).

In some embodiments, the absorber layer and/or the junction partner layer in a semiconductor junction 106/108 has a band gap between, *e.g.*, 0.6 eV (2066 nm) and 2.4 eV (516 nm), 0.7 eV (1771 nm) and 2.2 eV (563 nm), 0.8 eV (1550 nm) and 2.0 eV (620 nm), 0.9 eV (1378 nm) and 1.8 eV (689 nm), 1 eV (1240 nm) and 1.6 eV (775 nm), 1.1 eV (1127 nm) and 1.4 eV (886 nm), or 1.2 eV (1033 nm) and 1.3 eV (954 nm). In some embodiments, an absorber layer in a semiconductor junction 106/108 has a band gap between, *e.g.*, 0.6 eV (2066 nm) and 2.4 eV (516 nm), 0.7 eV (1771 nm) and 2.2 eV (563 nm), *e.g.*, 0.8 eV (1550 nm) and

2.0 eV (620 nm), 0.9 eV (1378 nm) and 1.8 eV (689 nm), 1 eV (1240 nm) and 1.6 eV (775 nm), 1.1 eV (1127 nm) and 1.4 eV (886 nm), or 1.2 eV (1033 nm) and 1.3 eV (954 nm). In some embodiments, a junction partner layer in a semiconductor junction 106/108 has a band gap between, *e.g.*, 0.6 eV (2066 nm) and 2.4 eV (516 nm), *e.g.*, 0.7 eV (1771 nm) and 2.2 eV (563 nm), 0.8 eV (1550 nm) and 2.0 eV (620 nm), *e.g.*, 0.9 eV (1378 nm) and 1.8 eV (689 nm), *e.g.*, 1 eV (1240 nm) and 1.6 eV (775 nm), 1.1 eV (1127 nm) and 1.4 eV (886 nm) or between, *e.g.*, 1.2 eV (1033 nm) and 1.3 eV (954 nm).

As noted above, the absorber layer and the junction partner layer include different semiconductors with different band gaps and electron affinities such that the junction partner layer has a larger band gap than the absorber layer. For example, the absorber may have a band gap between about 0.9 eV and about 1.8 eV. In some embodiments, the absorber layer in a semiconductor junction 106/108 includes copper-indium-gallium-diselenide (CIGS) and the band gap of the absorber layer is in the range of 1.04 eV to 1.67 eV. In some embodiments, the absorber layer in a semiconductor junction 106/108 includes copper-indium-gallium-diselenide (CIGS) and the minimum band gap of the absorber layer is between 1.1 eV and 1.2 eV.

In some embodiments the absorber layer in a semiconductor junction 106/108 is graded such that the band gap of the absorber layer varies as a function of absorber layer depth. As is known in the art, for the purposes of modeling, such a graded absorber layer can be modeled as stacked layers, each with a different composition and corresponding band gap. For instance, in some embodiments, the absorber layer in a semiconductor junction 106/108 includes copper-indium-gallium-diselenide having the stiochiometry $CuIn_{1-x}Ga_xSe_2$ with non-uniform Ga/In composition versus absorber layer depth. Such non-uniform Ga/In composition can be achieved, for example, by varying elemental fluxes of Ga and In during deposition of the absorber layer onto a nonplanar back-electrode. In some embodiments, the absorber layer in a semiconductor junction 106/108 includes copper-indium-gallium-diselenide with the stiochiometry $CuIn_{1-x}Ga_xSe_2$ in which the band gap ranges of the absorber varies between a first value in the range 1.04 eV to 1.67 eV and a second value in the range of 1.04 eV to 1.67 eV as a function of absorber depth, where the first value is greater than the second value. In some embodiments, the absorber layer in a semiconductor junction 106/108 includes copper-indium-gallium-diselenide having the stiochiometry $CuIn_{1-x}Ga_xSe_2$ in which the band gap of the absorber layer ranges between a first value in the range of 1.04 eV to 1.67 eV to a second value in the range of 1.04 eV to 1.67 eV as a function of absorber layer depth, where the first value is less than the second value. Typically, in such embodiments, the band gap ranges between the first value and the second value in a continuous linear gradient as a function of absorber layer depth. However, in some embodiments, the band gap ranges between the first value and the

second value in a nonlinear gradient or even a discontinuous fashion as a function of absorber layer depth.

In some embodiments, the absorber layer or the junction partner layer in a semiconductor junction 106/108 is characterized by a band gap that ranges between a first value in the range 1.04 eV to 1.67 eV to a second value in the range of 1.04 eV to 1.67 eV as a function of absorber layer depth, where the first value is greater than the second value. In some embodiments, the absorber layer in a semiconductor junction 106/108 includes copper-indium-gallium-diselenide having the stiochiometry $CuIn_{1-x}Ga_xSe_2$ in which the band gap ranges between a first value in the range of 1.04 eV to 1.67 eV to a second value in the range of 1.04 eV to 1.67 eV as a function of absorber depth, where the first value is less than the second value. In some embodiments, the band gap ranges between the first value and the second value in a continuous linear gradient as a function of absorber depth. However, in some embodiments, the band gap ranges between the first value and the second value in a nonlinear gradient or even a discontinuous fashion as a function of absorber depth. Moreover, in some embodiments, the band gap ranges between the first value and the second value in such a manner that the band gap increases and decreases a plurality of times as a function of absorber layer depth.

In some embodiments, the absorber layer or the junction partner layer in a semiconductor junction 106/108 of the present application is characterized by a band gap that ranges between a first value in the range of 0.6 eV (2066 nm) to 2.4 eV (516 nm) and a second value in the range of 0.6 eV (2066 nm) to 2.4 eV (516 nm), where the first value is less than the second value. In some embodiments, the absorber layer or the junction partner layer in a semiconductor junction 106/108 of the present application is characterized by a band gap that ranges between a first value in the range of 0.7 eV (1771 nm) to 2.2 eV (563 nm) and a second value in the range of 0.7 eV (1771 nm) to 2.2 eV (563 nm), where the first value is less than the second value. In some embodiments, the absorber layer or the junction partner layer in a semiconductor junction 106/108 of the present application is characterized by a band gap that ranges between a first value in the range of 0.8 eV (1550 nm) to 2.0 eV (620 nm) and a second value in the range of 0.8 eV (1550 nm) to 2.0 eV (620 nm), where the first value is less than the second value. In some embodiments, the absorber layer or the junction partner layer in a semiconductor junction 106/108 of the present application is characterized by a band gap that ranges between a first value in the range of 0.9 eV (1378 nm) to 1.8 eV (689 nm) and a second value in the range of 0.9 eV (1378 nm) to 1.8 eV (689 nm), where the first value is less than the second value. In some embodiments, the absorber layer or the junction partner layer in a semiconductor junction 106/108 of the present application is characterized by a band gap that

ranges between a first value in the range of 1 eV (1240 nm) to 1.6 eV (775 nm) and a second value in the range of 1 eV (1240 nm) to 1.6 eV (775 nm), where the first value is less than the second value. In some embodiments, the absorber layer or the junction partner layer in a semiconductor junction 106/108 of the present application is characterized by a band gap that ranges between a first value in the range of 1.1 eV (1127 nm) to 1.4 eV (886 nm) and a second value in the range of 1.1 eV (1127 nm) to 1.4 eV (886 nm), where the first value is less than the second value. In some embodiments, the absorber layer or the junction partner layer in a semiconductor junction 106/108 of the present application is characterized by a band gap that ranges between a first value in the range of 1.2 eV (1033 nm) to 1.3 eV (954 nm) and a second value in the range of 1.2 eV (1033 nm) to 1.3 eV (954 nm), where the first value is less than the second value. In some embodiments, the band gap ranges between the first value and the second value in a continuous linear gradient as a function of absorber layer or junction partner layer depth. However, in some embodiments, the band gap ranges between the first value and the second value in a nonlinear gradient or even a discontinuous fashion as a function of absorber layer depth or junction partner layer depth. Moreover, in some embodiments, the band gap ranges between the first value and the second value in such a manner that the band gap increases and decreases a plurality of times as a function of absorber layer or junction partner layer depth.

In some embodiments, the absorber layer or the junction partner layer in a semiconductor junction 106/108 of the present application is characterized by a band gap that ranges between a first value in the range of 0.6 eV (2066 nm) to 2.4 eV (516 nm) and a second value in the range of 0.6 eV (2066 nm) to 2.4 eV (516 nm), where the first value is greater than the second value. In some embodiments, the absorber layer or the junction partner layer in a semiconductor junction 106/108 of the present application is characterized by a band gap that ranges between a first value in the range of 0.7 eV (1771 nm) to 2.2 eV (563 nm) and a second value in the range of 0.7 eV (1771 nm) to 2.2 eV (563 nm), where the first value is greater than the second value. In some embodiments, the absorber layer or the junction partner layer in a semiconductor junction 106/108 of the present application is characterized by a band gap that ranges between a first value in the range of 0.8 eV (1550 nm) to 2.0 eV (620 nm) and a second value in the range of 0.8 eV (1550 nm) to 2.0 eV (620 nm), where the first value is greater than the second value. In some embodiments, the absorber layer or the junction partner layer in a semiconductor junction 106/108 of the present application is characterized by a band gap that ranges between a first value in the range of 0.9 eV (1378 nm) to 1.8 eV (689 nm) and a second value in the range of 0.9 eV (1378 nm) to 1.8 eV (689 nm), where the first value is greater than the second value. In some embodiments, the absorber layer or the junction partner layer in a

semiconductor junction 106/108 of the present application is characterized by a band gap that ranges between a first value in the range of 1 eV (1240 nm) to 1.6 eV (775 nm) and a second value in the range of 1 eV (1240 nm) to 1.6 eV (775 nm), where the first value is greater than the second value. In some embodiments, the absorber layer or the junction partner layer in a semiconductor junction 106/108 of the present application is characterized by a band gap that ranges between a first value in the range of 1.1 eV (1127 nm) to 1.4 eV (886 nm) and a second value in the range of 1.1 eV (1127 nm) to 1.4 eV (886 nm), where the first value is greater than the second value. In some embodiments, the absorber layer or the junction partner layer in a semiconductor junction 106/108 of the present application is characterized by a band gap that ranges between a first value in the range of 1.2 eV (1033 nm) to 1.3 eV (954 nm) and a second value in the range of 1.2 eV (1033 nm) to 1.3 eV (954 nm), where the first value is greater than the second value. In some embodiments, the band gap ranges between the first value and the second value in a continuous linear gradient as a function of absorber layer or junction partner layer depth. However, in some embodiments, the band gap ranges between the first value and the second value in a nonlinear gradient or even a discontinuous fashion as a function of absorber layer or junction partner layer depth. Moreover, in some embodiments, the band gap ranges between the first value and the second value in such a manner that the band gap increases and decreases a plurality of times as a function of absorber layer or junction partner layer depth.

The following table lists exemplary band gaps of several semiconductors suitable for use in semiconductor junctions such as those described herein, as well as some other physical properties of the semiconductors. "D" indicates a direct band gap, and "I" indicates an indirect band gap.

Table. Properties of various semiconductors (adapted from Pandey, *Handbook of Semiconductor Electrodeposition*, Marcel Dekker Inc., 1996, Appendix 5) that may be used in semiconductor junctions 410 of the present application

Material (type)	Density (g/cm^3)	Band gap (eV)	Gap transition	Electron Mobility ($cm^2V^1s^1$)	Hole Mobility ($cm^2V^1s^1$)	Dielectric Constant
B	—	1.53	I	6,000	4000	—
Si (*n,p*)	2.33	1.11	I	1,350	480	12
Ge (*n,p*)	5.33	0.66	I	3,600	1800	16
SiC (*n,p*)	3.22	2.75-3.1	I	60-120	10.2	4.84
CdS (*n,p*)	4.83	2.42	D	340	—	9-10.3
CdSe (*n*)	5.74	1.7	D	600	—	9.3-10
CdTe (*n,p*)	5.86	1.44	D	700	65	9.6
ZnS (*n*)	4.09	3.58	D	120	—	8.3
ZnSe (*n*)	5.26	2.67	D	530	—	9.1

Material (type)	Density (g/cm^3)	Band gap (eV)	Gap transition	Electron Mobility ($cm^2V^1s^1$)	Hole Mobility ($cm^2V^1s^1$)	Dielectric Constant
ZnTe (*p*)	5.70	2.26	D	530	130	10.1
HgSe	7.1-8.9	0.6	_	18,500	_	5.8
HgTe		0.025	_	22,000	160	_
PbS	7.5	0.37	I	600	200	_
PbSe	8.10	0.26	I	1,400	1400	_
PbTe (*n,p*)	8.16	0.29	I	6,000	4000	_
Bi_2S_3 (*n*)		1.3	I	200	_	_
Sb_2Se_3		1.2	_	15	45	_
Sb_2S_3		1.7	_	_	_	_
As_2Se_3		1.6	_	15	45	_
In_2S_3		2.28	_	_	_	_
In_2Se_3		1.25	_	30	_	_
Mg_2Si		0.77	_	370	65	_
$ZnAs_2$		0.9	_	_	50	_
$CdAs_2$		1.0	_	_	100	_
AlAs (*n,p*)	3.79	2.15	I	_	280	10.1
AlSb (*n,p*)	4.26	1.6	I	900	400	10.3
GaAs (*n,p*)	5.32	1.43	D	58,000	300	11.5
GaSb (*n,p*)	5.60	0.68	D	5,000	1000	14.8
GaP (*n,p*)	4.13	2.3	D	110	75	8.5
InP (*n,p*)	4.78	1.27	D	4,500	100	12.1
InSb (*n,p*)	5.77	0.17	D	80,000	450	15.07
InAs (*n,p*)	5.60	0.36	D	33,000	450	11.7
MoS_2 (*n,p*)	4.8	1.75	I,D	_	200	_
$MoSe_2$ (*n,p*)		1.4	I,D	10-50	_	_
$MoTe_2$ (*n,p*)		1.0	I	_	_	_
WSe_2 (*n,p*)		1.57	I	100-150	_	_
$ZrSe_2$ (*p*)		1.05-1.22	I	_	_	_
$CuInS_2$ (*n,p*)	4.75	1.3-1.5	_	_	_	_
$CuInSe_2$ (*n,p*)	5.77	0.9-1.11	_	_	_	_
$CuGaS_2$ (*p*)	4.35	2.1	_	_	_	_
$CuGaSe_2$ (*p*)	5.56	1.5	_	_	_	_
$CuInS_{0.5}Se_{1.5}$ (*p*)		1.5	_	_	_	_
CuInSSe (*p*)		1.2	_	_	_	_
$CuInS_{1.5}S_{o.5}$ (*n,p*)		1.3	_	_	_	_
$CuGa_{0.5}In_{0.5}S_2$ (*p*)		1.4	_	_	_	_
$CuGA_{0.5}In_{0.5}Se_2$ (*p*)		1.1	_	_	_	_
$CuGa_{0.75}In_{0.25}Se_2$ (*p*)		1.35	_	_	_	_
$CuGa_{0.25}In_{0.75}Se_2$		1.0	_	_	_	_
$CuGa_{0.5}In_{0.5}SSe$ (*p*)		1.2	_	_	_	_
$CuGa_{0.25}In_{0.75}S_{0.5}Se_{1..5}$ (*p*)		1.0	_	_	_	_
$CuGa_{0.75}In_{0.25}SSe_{1.5}$ (*p*)		1.1	_	_	_	_
$Cu_2CdSnSe_4$ (*p*)		1.5	_	_	_	_
$CuInSnS_4$ (*p*)		1.1	_	_	_	_
$CuInSnSe_4$ (*p*)		0.9	_	_	_	_

Material (type)	Density (g/cm^3)	Band gap (eV)	Gap transition	Electron Mobility ($cm^2V^1s^1$)	Hole Mobility ($cm^2V^1s^1$)	Dielectric Constant
$CuIn_5Se_8(p)$		1.3	–	–	–	–
$CuGa_3S_5$ (p)		1.8	–	–	–	–
$CuGa_5Se_8$ (p)		2.0	–	–	–	–
$CuGa_5Se_8$		1.2	–	–	–	–
$CuGa_{2.5}In_{2.5}S_4Se_8$		1.4	–	–	–	–

In some embodiments, the density of the semiconductor materials in the absorber layer and/or the junction partner of a semiconductor junction 106/108 ranges between about 2.33 g/cm^3 and8.9 g/cm^3.. In some embodiments, the absorber layer has a density of between about 5 g/cm^3 and 6 g/cm^3. In some embodiments the absorber layer includes CIGS. The density of CIGS changes with its composition because the unit crystal cell changes from cubic to tetragonal. The chemical formula for CIGS is: $Cu(In_{1-x}Ga_x)Se_2$. At gallium mole fractions below 0.5, the CIGS takes on a tetragonal chalcopyrite structure. At mole fractions above 0.5, the cell structure is cubic zinc-blende. In some embodiments, the absorber layer of a semiconductor junction 106/108 includes CIGS in which the mole fraction (x) is between 0.2 and 0.6, a density of between 5 g/cm^3 and 6 g/cm^3 and a band gap between about 1.2 eV and 1.4 eV. In an embodiment, the absorber layer of a semiconductor junction 106/108 includes CIGS in which the mole fraction (x) is between 0.2 and 0.6, the density of the CIGS is between 5 g/cm^3 and 6 g/cm^3 and the band gap of the CIGS is between about 1.2 eV and 1.4 eV. In an embodiment, the absorber layer of a semiconductor junction 106/108 includes CIGS in which the mole fraction (x) is 0.4, the density of the CIGS is about 5.43 g/cm^3, and the band gap of the CIGS is about 1.2 eV.

Current Densities. The combination of materials used in the semiconductor junction, *e.g.*, absorber layer and junction partner layer, are selected to generate a sufficient current density (also commonly called the "short circuit current density," or J_{sc}) upon irradiation with photons with energies at or above the band gap of the absorber layer, to efficiently produce electricity. In order to enhance J_{sc}, it is desirable to (1) absorb as much of the incident light as possible, *e.g.*, to have a small band gap with high absorption over a wide energy range, and (2) to have material properties such that the photoexcited electrons and holes are able to be collected by the internal electric field generated by the junction and pass into an external circuit before they recombine, *e.g.*, a material with a high minority carrier lifetime and mobility. At the same time, the band gap of the junction partner layer is usefully large relative to that of the absorber layer so that the bulk of the photon absorption occurs in the absorber layer. For example, in some embodiments, the compounds in the semiconductor junction 106/108 (*e.g.*, the absorber layer and/or the junction partner layer) are selected such that the solar cell

generates a current density J_{sc} of at least 10 mA/cm^2, at least 15 mA/cm^2, at least 20 mA/cm^2, at least 25 mA/cm^2, at least 30 mA/cm^2, at least 35 mA/cm^2, or at least 39 mA/cm^2 upon irradiation with an air mass (AM) 1.5 global spectrum, an AM1.5 direct terrestrial spectra, an AM0 reference spectra as defined in Section 16.2.1 of *Handbook of Photovoltaic Science and Engineering*, 2003, Luque and Hegedus (eds.), Wiley & Sons, West Sussex, England (2003), which is hereby incorporated by reference herein. The air-mass value 0 equates to insolation at sea level with the Sun at its zenith, as shown, AM 1.0 represents sunlight with the Sun at zenith above the Earth's atmosphere and absorbing oxygen and nitrogen gases, AM 1.5 is the same, but with the Sun at an oblique angle of 48.2°, which simulates a longer optical path through the Earth's atomosphere, and AM 2.0 extends that oblique angle to 60.1°. See Jeong, 2007, Laser Focus World 43, 71-74, which is hereby incorporated by reference herein.

In some embodiments, the solar cells of the present invention exhibit a J_{sc}, when measured under standard conditions (25 °C, AM 1.5 G 100 mW/cm^2), that is between 22 mA/cm^2 and 35 mA/cm^2. In some embodiments, the solar cells of the present invention exhibit a J_{sc}, when measured under AM 1.5 G, that is between 22 mA/cm^2 and 35 mA/cm^2 at any temperature between 0°C and 70°C. In some embodiments, the solar cells of the present invention exhibit a J_{sc}, when measured under AM 1.5 G conditions, that is between 22 mA/cm^2 and 35 mA/cm^2 at any temperature between 10°C and 60°C. For computing current density, illumination intensities are calibrated, for example, by the standard amorphous Si solar cell in the manner used to report values in Nishitani *et al.*, 1998, Solar Energy Materials and Solar Cells 50, p. 63-70 and the references cited therein, which is hereby incorporated by reference in its entirety.

In some embodiments, the materials of the absorber layer and/or the junction partner layer of the semiconductor junction 106/108 have electron mobilities between, *e.g.*, 10 $cm^2V^1s^1$ and 80,000 10 $cm^2V^1s^1$.

Open circuit voltage. In some embodiments, the solar cells of the present invention exhibit an open circuit voltage V_{oc} (V), when measured under standard conditions (25 °C, AM 1.5 G 100 mW/cm^2), that is between 0.4V and 0.8V. In some embodiments, the solar cells of the present invention exhibit an V_{oc}, when measured under AM 1.5 G, that is between 0.4V and 0.8V at any temperature between 0°C and 70°C. In some embodiments, the solar cells of the present invention exhibit a V_{oc}, when measured under AM 1.5 G conditions, that is between 0.4V and 0.8V at any temperature between 10°C and 60°C. For computing open circuit voltage, illumination intensities are calibrated, for example, by the standard amorphous Si solar cell in the manner used to report values in Nishitani *et al.*, 1998, Solar Energy Materials and Solar Cells 50, p. 63-70 and the references cited therein, which is hereby incorporated by

reference in its entirety.

1.3.1 Thin-film semiconductor junctions based on copper indium diselenide and other type I-III-VI materials

Continuing to refer to Figure 10A, in some embodiments, the absorber layer 106 is a group I-III-VI_2 compound such as copper indium di-selenide ($CuInSe_2$; also known as CIS). In some embodiments, the absorber layer 106 is a group I-III-VI_2 ternary compound selected from the group consisting of $CdGeAs_2$, $ZnSnAs_2$, $CuInTe_2$, $AgInTe_2$, $CuInSe_2$, $CuGaTe_2$, $ZnGeAs_2$, $CdSnP_2$, $AgInSe_2$, $AgGaTe_2$, $CuInS_2$, $CdSiAs_2$, $ZnSnP_2$, $CdGeP_2$, $ZnSnAs_2$, $CuGaSe_2$, $AgGaSe_2$, $AgInS_2$, $ZnGeP_2$, $ZnSiAs_2$, $ZnSiP_2$, $CdSiP_2$, or $CuGaS_2$ of either the *p*-type or the *n*-type when such compound is known to exist.

In some embodiments, the junction partner layer 108 is CdS, ZnS, ZnSe, or CdZnS. In one embodiment, the absorber layer 106 is *p*-type CIS and the junction partner layer 108 is *n*-type CdS, ZnS, ZnSe, or CdZnS. Such semiconductor junctions 106/108 are described in Chapter 6 of Bube, *Photovoltaic Materials*, 1998, Imperial College Press, London, which is incorporated by reference herein in its entirety.

In some embodiments, the absorber layer 106 is copper-indium-gallium-diselenide (CIGS). Such a layer is also known as $Cu(InGa)Se_2$. In some embodiments, the absorber layer 106 is copper-indium-gallium-diselenide (CIGS) and the junction partner layer 108 is CdS, ZnS, ZnSe, or CdZnS. In some embodiments, the absorber layer 106 is *p*-type CIGS and the junction partner layer 108 is *n*-type CdS, ZnS, ZnSe, or CdZnS. Such semiconductor junctions 106/108 are described in Chapter 13 of *Handbook of Photovoltaic Science and Engineering*, 2003, Luque and Hegedus (eds.), Wiley & Sons, West Sussex, England, Chapter 12, which is incorporated by reference herein in its entirety. In some embodiments, CIGS is deposited using techniques disclosed in Beck and Britt, Final Technical Report, January 2006, NREL/SR-520-39119; and Delahoy and Chen, August 2005, "Advanced CIGS Photovoltaic Technology," subcontract report; Kapur *et al.*, January 2005 subcontract report, NREL/SR-520-37284, "Lab to Large Scale Transition for Non-Vacuum Thin Film CIGS Solar Cells"; Simpson *et al.*, October 2005 subcontract report, "Trajectory-Oriented and Fault-Tolerant-Based Intelligent Process Control for Flexible CIGS PV Module Manufacturing," NREL/SR-520-38681; and Ramanathan *et al.*, 31st IEEE Photovoltaics Specialists Conference and Exhibition, Lake Buena Vista, Florida, January 3-7, 2005, each of which is hereby incorporated by reference herein in its entirety.

In some embodiments the absorber layer 106 is CIGS grown on a molybdenum conducting material 104 by evaporation from elemental sources in accordance with a three

stage process described in Ramanthan *et al.*, 2003, "Properties of 19.2 % Efficiency ZnO/CdS/CuInGaSe$_2$ Thin-film Solar Cells," Progress in Photovoltaics: Research and Applications 11, 225, which is hereby incorporated by reference herein in its entirety. In some embodiments, the layer 504 is a ZnS(O,OH) buffer layer as described, for example, in Ramanathan *et al.*, Conference Paper, "CIGS Thin-Film Solar Research at NREL: FY04 Results and Accomplishments," NREL/CP-520-37020, January 2005, which is hereby incorporated by reference herein in its entirety.

In some embodiments, the absorber layer 106 is between 0.5 μm and 2.0 μm thick. In some embodiments, the composition ratio of Cu/(In+Ga) in the layer 106 is between 0.7 and 0.95. In some embodiments, the composition ratio of Ga/(In+Ga) in the layer 106 is between 0.2 and 0.4. In some embodiments, the absorber layer 106 is CIGS that has a <110> crystallographic orientation. In some embodiments, the absorber layer 106 is CIGS that has a <112> crystallographic orientation. In some embodiments, the absorber layer 106 is CIGS in which the CIGS crystals are randomly oriented.

1.3.2 Semiconductor junctions based on amorphous silicon or polycrystalline silicon

In some instances, layers having reference numerals other than 106 and 108 are used to describe layers that may be in a semiconductor junction 106/108. It will be appreciated that such layers can be used instead of the layers 106 and 108 that are depicted in Figure 2. In some embodiments, the semiconductor junction 106/108 comprises amorphous silicon. In some embodiments, this is an n/n type heterojunction. For example, in some embodiments, referring to Figure 10B, the semiconductor junction 106/108 comprises SnO_2(Sb), the layer 512 comprises undoped amorphous silicon, and the layer 510 comprises *n*+ doped amorphous silicon.

In some embodiments, the semiconductor junction 106/108 is a *p-i-n* type junction. For example, in some embodiments, the semiconductor junction 106/108 comprises a layer 514 that is p^+ doped amorphous silicon, a layer 512 that is undoped amorphous silicon, and a layer 510 that is n^+ amorphous silicon. Such semiconductor junctions 106/108 are described in Chapter 3 of Bube, *Photovoltaic Materials*, 1998, Imperial College Press, London, which is hereby incorporated by reference herein in its entirety.

In some embodiments, the semiconductor junction 106/108 is based upon thin-film polycrystalline. Referring to Figure 10B, in one example in accordance with such embodiments, layer 510 is a *p*-doped polycrystalline silicon, layer 512 is depleted polycrystalline silicon and layer 514 is *n*-doped polycrystalline silicon. Such semiconductor junctions are described in Green, *Silicon Solar Cells: Advanced Principles & Practice*, Centre

for Photovoltaic Devices and Systems, University of New South Wales, Sydney, 1995; and Bube, *Photovoltaic Materials*, 1998, Imperial College Press, London, pp. 57-66, which is hereby incorporated by reference in its entirety.

In some embodiments, the semiconductor junction 106/108 is based upon *p*-type microcrystalline Si:H and microcrystalline Si:C:H in an amorphous Si:H context. Such semiconductor junctions are described in Bube, *Photovoltaic Materials*, 1998, Imperial College Press, London, pp. 66-67, and the references cited therein, which is hereby incorporated by reference herein in its entirety.

In some embodiments, the semiconductor junction 106/108 is a tandem junction. Tandem junctions are described in, for example, Kim *et al.*, 1989, "Lightweight (AlGaAs)GaAs/CuInSe2 Tandem Junction Solar Cells for Space Applications," Aerospace and Electronic Systems Magazine, IEEE Volume 4, pp: 23–32; Deng, 2005, "Optimization of a-SiGe Based Triple, Tandem and Single-junction Solar Cells," Photovoltaic Specialists Conference, Conference Record of the Thirty-first IEEE, pp: 1365–1370; Arya *et al.*, 2000, "Amorphous Silicon Based Tandem Junction Thin-film Technology: a Manufacturing Perspective," Photovoltaic Specialists Conference, 2000, Conference Record of the Twenty-Eighth IEEE 15-22, pp: 1433–1436; Hart, 1988, "High Altitude Current-voltage Measurement of GaAs/Ge solar cells," Photovoltaic Specialists Conference, Conference Record of the Twentieth IEEE 26-30, pp:764-765, vol.1; Kim, 1988, "High Efficiency GaAs/$CuInSe_2$ Tandem Junction Solar Cells," Photovoltaic Specialists Conference, Conference Record of the Twentieth IEEE 26-30, pp: 457-461 vol.1; Mitchell, 1988, "Single and Tandem Junction $CuInSe_2$ Cell and Module Technology," Photovoltaic Specialists Conference, Conference Record of the Twentieth IEEE 26-30, pp: 1384-1389, vol.2; and Kim, 1989, "High Specific Power (AlGaAs)GaAs/$CuInSe_2$ Tandem Junction Solar Cells for Space Applications," Energy Conversion Engineering Conference, IECEC-89, Proceedings of the 24th Intersociety 6-11, pp: 779-784, vol.2, each of which is hereby incorporated by reference herein in its entirety.

1.3.3 Semiconductor junctions based on gallium arsenide and other type III-V materials

In some embodiments, the semiconductor junction 106/108 is based upon gallium arsenide (GaAs) or other III-V materials such as InP, AlSb, and CdTe. GaAs is a direct-band gap material having a band gap of 1.43 eV and can absorb 97% of AM1 radiation in a thickness of about two microns. Suitable type III-V junctions that can serve as semiconductor junctions 106/108 are described in Chapter 4 of Bube, *Photovoltaic Materials*, 1998, Imperial College Press, London, which is hereby incorporated by reference herein in its entirety.

Furthermore, in some embodiments, the semiconductor junction 106/108 is a hybrid

multijunction solar cell such as a GaAs/Si mechanically stacked multijunction as described by Gee and Virshup, 1988, 20th *IEEE Photovoltaic Specialist Conference*, IEEE Publishing, New York, p. 754, which is incorporated by reference herein in its entirety, a GaAs/$CuInSe_2$ MSMJ four-terminal device, consisting of a GaAs thin film top cell and a ZnCdS/$CuInSe_2$ thin bottom cell described by Stanbery *et al.*, 19th *IEEE Photovoltaic Specialist Conference*, IEEE Publishing, New York, p. 280, and Kim *et al.*, 20th *IEEE Photovoltaic Specialist Conference*, IEEE Publishing, New York, p. 1487, each of which is hereby incorporated by reference herein in its entirety. Other hybrid multijunction solar cells are described in Bube, *Photovoltaic Materials*, 1998, Imperial College Press, London, pp. 131-132, which is hereby incorporated by reference herein in its entirety.

1.3.4 Semiconductor junctions based on cadmium telluride and other type II-VI materials

In some embodiments, the semiconductor junction 106/108 is based upon II-VI compounds that can be prepared in either the *n*-type or the *p*-type form. Accordingly, in some embodiments, referring to Figure 10C, the semiconductor junction 106/18 is a *p-n* heterojunction in which the layers 106 and 108 are any combination set forth in the following table or alloys thereof.

Layer 106	Layer 108
n-CdSe	*p*-CdTe
n-ZnCdS	*p*-CdTe
n-ZnSSe	*p*-CdTe
p-ZnTe	*n*-CdSe
n-CdS	*p*-CdTe
n-CdS	*p*-ZnTe
p-ZnTe	*n*-CdTe
n-ZnSe	*p*-CdTe
n-ZnSe	*p*-ZnTe
n-ZnS	*p*-CdTe
n-ZnS	*p*-ZnTe

Methods for manufacturing a semiconductor junction 106/108 that is based upon II-VI compounds is described in Chapter 4 of Bube, *Photovoltaic Materials*, 1998, Imperial College Press, London, which is hereby incorporated by reference herein in its entirety for such purpose.

1.3.5 Semiconductor junctions based on crystalline silicon

While semiconductor junctions 106/108 that are made from thin film semiconductor films are preferred, the disclosure is not so limited. In some embodiments the semiconductor junctions 106/108 are based upon crystalline silicon. For example, referring to Figure 5D, in some embodiments, the semiconductor junction 106/108 comprises a layer of *p*-type crystalline silicon 106 and a layer of *n*-type crystalline silicon 108. Methods for manufacturing such crystalline silicon semiconductor junctions 106/108 are described in Chapter 2 of Bube, *Photovoltaic Materials*, 1998, Imperial College Press, London, which is hereby incorporated by reference herein in its entirety.

1.4 EXEMPLARY DIMENSIONS

As illustrated in Figures 2 and 3A, a nonplanar photovoltaic device 10 has a length *l* that is great compared to the diameter *d* of its cross-section. In some embodiments, a photovoltaic device 10 has a length *l* between 1 centimeter (cm) and 50,000 cm and a width *d* between 1 cm and 50,000 cm. In some embodiments, a photovoltaic device 10 has a length *l* between 10 cm and 1,000 cm and a width *d* between 10 cm and 1,000 cm. In some embodiments, a photovoltaic device 10 has a length *l* between 40 cm and 500 cm and a width *d* between 40 cm and 500 cm.

In some embodiments, a photovoltaic device 10 has the planar configuration illustrated in Figure 8A. Referring to Figure 4A, in such embodiments, the photovoltaic device 10 may have a length *x* of between 1 centimeter and 10,000 centimeters. Further, the photovoltaic device 10 may have a width of between 1 centimeter and 10,000 centimeters.

In some embodiments, a photovoltaic device 10 may be elongated as illustrated in Figure 3. As illustrated in Figure 3, an elongated photovoltaic device 10 is one that is characterized by having a longitudinal dimension *l* and a width dimension *d*. In some embodiments of an elongated photovoltaic device 10, the longitudinal dimension *l* exceeds the width dimension *d* by at least a factor of 4, at least a factor of 5, or at least a factor of 6. In some embodiments, the longitudinal dimension *l* of the elongated photovoltaic device is 10 centimeters or greater, 20 centimeters or greater, 100 centimeters or greater. In some embodiments, the width dimension *d* of the elongated photovoltaic device 10 is a width of 500 millimeters or more, 1 centimeter or more, 2 centimeters or more, 5 centimeters or more, or 10 centimeters or more.

The solar cells 12 of the photovoltaic devices 10 may be made in various ways and have various thicknesses. The solar cells 12 as described herein may be so-called thick-film semiconductor structures or a so-called thin-film semiconductor structures.

In some embodiments, a container 25 has a length *l* that is great compared to the diameter *d* of its cross-section. In some embodiments, a container 25 has a length between 1 cm and 50,000 cm and a width between 1 cm and 50,000 cm. In some embodiments, a container 25 has a length *l* between 10 cm and 1,000 cm and a width between 10 cm and 1,000 cm. In some embodiments, a container has a length between 40 cm and 500 cm and a width *d* between 40 cm and 500 cm. In some embodiments, a container 25 is dimensioned to have a container volume of at least one cubic centimeter, at least 10 cubic centimeters, at least 20 cubic centimeters, at least 30 cubic centimeters, at least 50 cubic centimeters, at least 100 cubic centimeters, or at least 1000 cubic.

1.5 EXEMPLARY EMBODIMENTS

One aspect of the disclosure provides a photovoltaic device comprising (i) an outer transparent casing, (ii) a substrate, the substrate and the outer transparent casing defining an inner volume, (iii) at least one solar cell disposed on the substrate, (iv) a filler layer that seals the at least one solar cell within the inner volume, (v) a container within the inner volume. The container is configured to decrease in volume when the filler layer thermally expands, and increase in volume when the filler layer thermally contracts. In some instances, the container comprises a sealed container having a plurality of ridges. In some instances, each ridge in the plurality of ridges is uniformly spaced apart. In some instances, ridges in the plurality of ridges are not uniformly spaced apart. In some instances, the container is made of flexible plastic or thin malleable metal.

In some embodiments, the container has a container volume of at least one cubic centimeter, at least 30 cubic centimeters, or at least 100 cubic centimeters. In some embodiments, the container has an opening and wherein that is sealed by a spring loaded seal. In some instances, the container has a first opening and a second opening. In such embodiments, the first opening is sealed by a first spring loaded seal and the second opening is sealed by a second spring loaded seal.

In some embodiments, the container is a balloon. In some embodiments, the container is made of rubber, latex, chloroprene or a nylon fabric. In some embodiments, the container has an elongated asteroid shape. In some embodiments, the container is made of brushed metal. In some embodiments, the substrate is planar and the container is immersed in the filler layer. In some embodiments, the substrate is cylindrical and the container is immersed in the filler layer between a solar cell in the at least one solar cell and the outer transparent casing. In some embodiments, the outer transparent casing is tubular and encapsulates the substrate. In some embodiments, the substrate has a hollow core and the container is formed in the hollow core. In

some embodiments, the filler layer has a volumetric thermal coefficient of expansion of greater than 250 x 10^{-6} / °C or greater than 500 x 10^{-6} / °C.

In some embodiments, a solar cell in the at least one solar cell comprises a conducting material disposed on the substrate, a semiconductor junction disposed on said conducting material, and a transparent conducting layer disposed on the semiconductor junction. In some embodiments, the semiconductor junction comprises a homojunction, a heterojunction, a heteroface junction, a buried homojunction, a *p-i-n* junction, or a tandem junction. In some embodiments, the semiconductor junction comprises an absorber layer and a junction partner layer, wherein said junction partner layer is disposed on the absorber layer. In some embodiments, the absorber layer is copper-indium-gallium-diselenide and said junction partner layer is In_2Se_3, In_2S_3, ZnS, ZnSe, CdInS, CdZnS, $ZnIn_2Se_4$, $Zn_{1-x}Mg_xO$, CdS, SnO_2, ZnO, ZrO_2, or doped ZnO.

In some embodiments, the photovoltaic device further comprises an antireflective coating disposed on the outer transparent casing. In some embodiments, the antireflective coating comprises MgF_2, silicone nitrate, titanium nitrate, silicon monoxide, or silicone oxide nitrite. In some embodiments, the substrate comprises plastic or glass. In some embodiments, the substrate comprises metal or metal alloy. In some embodiments, the photovoltaic device further comprises an additional one or more containers, and each respective container in the additional one or more containers is within the inner volume.

In some embodiments, the at least one solar cell comprises a plurality of solar cells that are monolithically integrated onto the substrate. In some embodiments, a first solar cell in the plurality of solar cells is electrically connected in series to a second solar cell in the plurality of solar cells. In some embodiments, a first solar cell in the plurality of solar cells is electrically connected in parallel to a second solar cell in the plurality of solar cells.

In some embodiments, the container undergoes up to a five percent, up to a ten percent, up to a twenty percent, or up to a forty percent reduction in container volume between when the filler layer is in a first thermally expanded state and when the filler layer is in a second thermally contracted state.

One aspect of the disclosure provides a photovoltaic device comprising (i) an outer transparent casing, (ii) a substrate, the substrate and the outer transparent casing defining an inner volume, (iii) at least one solar cell disposed on the substrate, (iv) a filler layer that seals the at least one solar cell within the inner volume, and (v) a container within the inner volume; where the container comprises a sealed container having a plurality of ridges, and where the container is configured to decrease the container volume when the filler layer thermally expands and increase the container volume when the filler layer thermally contracts.

Another aspect of the disclosure comprises (i) an outer transparent casing, (ii) a substrate, the substrate and the outer transparent casing defining an inner volume, (iii) at least one solar cell disposed on the substrate, (iv) a filler layer that seals the at least one solar cell within the inner volume, (v) a container within the inner volume, where the container has a first opening that is sealed by a spring loaded seal, and where the container is configured to decrease the container volume when the filler layer thermally expands and increase the container volume when the filler layer thermally contracts.

Another aspect of the disclosure comprises a photovoltaic device comprising (i) an outer transparent casing, (ii) a substrate, the substrate and the outer transparent casing defining an inner volume, (iii) at least one solar cell disposed on the substrate, (iv) a filler layer that seals the at least one solar cell within the inner volume, and (v) a container within the inner volume, where the container has a first opening and a second opening, where the first opening is sealed by a first spring loaded seal and the second opening is sealed by a second spring loaded seal. The container is configured to decrease the container volume when the filler layer thermally expands and increase the container volume when the filler layer thermally contracts.

Still another aspect of the disclosure comprises (i) an outer transparent casing, (ii) a substrate, the substrate and the outer transparent casing defining an inner volume, (iii) at least one solar cell disposed on the substrate, (iv) a filler layer that seals the at least one solar cell within the inner volume, and (v) a container within the inner volume, where the container is a balloon that is configured to decrease the container volume when the filler layer thermally expands and increase the container volume when the filler layer thermally contracts.

Yet another aspect of the disclosure comprises a photovoltaic device comprising (i) an outer transparent casing, (ii) a substrate, the substrate and the outer transparent casing defining an inner volume, (iii) at least one solar cell disposed on the substrate, (iv) a filler layer that seals the at least one solar cell within the inner volume, and (v) a container within the inner volume. The container has an elongated asteroid shape and is configured to decrease the container volume when the filler layer thermally expands and increase the container volume when the filler layer thermally contracts.

REFERENCES CITED AND CONCLUSION

All references cited herein are incorporated herein by reference in their entirety and for all purposes to the same extent as if each individual publication or patent or patent application was specifically and individually indicated to be incorporated by reference in its entirety for all purposes.

Many modifications and variations of this invention can be made without departing from its spirit and scope, as will be apparent to those skilled in the art. The specific embodiments described herein are offered by way of example only, and the invention is to be limited only by the terms of the appended claims, along with the full scope of equivalents to which such claims are entitled.

WHAT IS CLAIMED:

1. A photovoltaic device comprising:

a) an outer transparent casing;

b) a substrate, wherein the substrate and the outer transparent casing define an inner volume;

c) at least one solar cell disposed on the substrate;

d) a filler layer comprising a filler composition that seals the at least one solar cell within the inner volume; and

e) a first container within the inner volume;

wherein the first container is configured to:

decrease the container volume when the filler layer thermally expands, and

increase the container volume when the filler layer thermally contracts.

2. The photovoltaic device of claim 1, wherein the first container comprises a sealed container having a plurality of ridges.

3. The photovoltaic device of claim 2, wherein each ridge in the plurality of ridges is uniformly spaced apart on a surface of the first container.

4. The photovoltaic device of claim 2, wherein ridges in the plurality of ridges are not uniformly spaced apart on a surface of the first container.

5. The photovoltaic device of any one of claims 1-4, wherein the first container is made of a plastic or a metal.

6. The photovoltaic device of any one of claims 1-5, wherein the first container has a container volume of at least one cubic centimeter.

7. The photovoltaic device of any one of claims 1-6, wherein the first container has a first opening and wherein the first opening is sealed by a spring loaded seal.

8. The photovoltaic device of any one of claims 1-6, wherein the first container has a first opening and a second opening, wherein,

the first opening is sealed by a first spring loaded seal; and

the second opening is sealed by a second spring loaded seal.

9. The photovoltaic device of any one of claims 1-6, wherein the first container is a balloon.

10. The photovoltaic device of any one of claims 1-9, wherein the first container is made of rubber, latex, chloroprene or a nylon fabric.

11. The photovoltaic device of any one of claims 1-10, wherein the first container has an elongated asteroid shape.

12. The photovoltaic device of any one of claims 1-9, or 11, wherein the first container is made of brushed metal.

13. The photovoltaic device of any one of claims 1-12, wherein the substrate is planar and the first container is immersed in the filler layer.

14. The photovoltaic device of any one of claims 1-12, wherein the substrate is nonplanar and the first container is immersed in the filler layer between a solar cell in the at least one solar cell and the outer transparent casing.

15. The photovoltaic device of any one of claims 1-14, wherein the outer transparent casing is tubular and encapsulates the substrate.

16. The photovoltaic device of any one of claims 1-15, wherein the substrate has a hollow core and the first container is formed in the hollow core.

17. The photovoltaic device of any one of claims 1-16, wherein the filler composition has a volumetric thermal coefficient of expansion of greater than 250 x 10^{-6}/ °C.

18. The photovoltaic device of any one of claims 1-17, wherein a solar cell in the at least one solar cell comprises:

a conducting material disposed on the substrate;

a semiconductor junction disposed on all or a portion of said conducting material; and

a transparent conducting layer disposed on all or a portion of said semiconductor junction.

19. The photovoltaic device of claim 18, wherein the semiconductor junction comprises a homojunction, a heterojunction, a heteroface junction, a buried homojunction, a *p-i-n* junction, or a tandem junction.

20. The photovoltaic device of claim 18, wherein said semiconductor junction comprises an absorber layer and a junction partner layer, wherein said junction partner layer is disposed on said absorber layer.

21. The photovoltaic device of claim 20, wherein said absorber layer is copper-indium-gallium-diselenide and said junction partner layer is In_2Se_3, In_2S_3, ZnS, ZnSe, CdInS, CdZnS, $ZnIn_2Se_4$, $Zn_{1-x}Mg_xO$, CdS, SnO_2, ZnO, ZrO_2, or doped ZnO.

22. The photovoltaic device of any one of claims 1-21, further comprising an antireflective coating disposed on the outer transparent casing.

23. The photovoltaic device of claim 22, wherein the antireflective coating comprises MgF_2, silicone nitrate, titanium nitrate, silicon monoxide, or silicone oxide nitrite.

24. The photovoltaic device of any one of claims 1-23, wherein the substrate comprises plastic or glass.

25. The photovoltaic device of any one of claims 1-23, wherein the substrate comprises metal or metal alloy.

26. The photovoltaic device of any one of claims 1-25, further comprising an additional one or more containers, and wherein each respective container in the additional one or more containers is within the inner volume.

27. The photovoltaic device of any one of claims 1-26, wherein the at least one solar cell comprises a plurality of solar cells that are monolithically integrated onto the substrate.

28. The photovoltaic device of claim 27, wherein a first solar cell in the plurality of solar cells is electrically connected in series to a second solar cell in the plurality of solar cells.

29. The photovoltaic device of claim 27, wherein a first solar cell in the plurality of solar cells is electrically connected in parallel to a second solar cell in the plurality of solar cells.

30. The photovoltaic device of any one of claims 1-29, wherein the first container undergoes up to a five percent reduction in container volume between (i) when the filler layer is in a first thermally expanded state and (ii) when the filler layer is in a second thermally contracted state.

31. The photovoltaic device of any one of claims 1-29, wherein the first container undergoes up to a forty percent reduction in container volume between (i) when the filler layer is in a first thermally expanded state and (ii) when the filler layer is in a second thermally contracted state.

32. The photovoltaic device of any one of claims 1-31, wherein the substrate or the outer transparent casing is rigid.

33. The photovoltaic device of any one of claims 1-32, wherein the substrate or the outer transparent casing is made of a linear material.

34. The photovoltaic device of any one of claims 1-33, wherein the substrate or the outer transparent casing has a Young's modulus of 40 GPa or greater.

35. The photovoltaic device of any one of claims 1-34, wherein the first container is under less than 500 Torr of pressure.

36. The photovoltaic device of any one of claims 1-35, wherein the first container contains an inert gas.

37. The photovoltaic device of claim 1, wherein the substrate is planar.

38. The photovoltaic device of claim 1, wherein the at least one solar cell is circumferentially disposed on the substrate.

39. The photovoltaic device of any one of claims 1-38, wherein the photovoltaic device is elongated.

40. The photovoltaic device of claim 1, wherein the substrate is characterized by a

cross-section having a bounding shape, wherein the bounding shape is circular, elliptical, a polygon, ovoid, or wherein the bounding shape is characterized by one or more smooth curved surfaces, or one or more arcuate edges.

41. The photovoltaic device of any one of claims 1-40, wherein the filler layer is a gel.

42. The photovoltaic device of any one of claims 1-40, wherein the filler layer is a liquid.