

## PROTECTIVE BARRIER LAYERS FOR PHOTOVOLTAIC MODULES

## Cross Reference To Related Applications

[0001] This application claims the benefit of priority to U.S. provisional patent application No. 63/603,987, filed on November 29, 2023; the entirety of which is hereby incorporated by reference herein.

## BACKGROUND OF THE INVENTION

## Field of the Invention

[0002] The invention relates to protective barrier layers for stable interconnects in perovskite photovoltaic modules.

## Background

[0003] Interconnects are used in thin film photovoltaic modules to minimize the effect of the electrode series resistance on module performance. The result of the interconnects is to configure the module into smaller sub-cells that are connected in series across the module through the P1, P2 and P3 scribes. The P1-scribe is used to isolate regions of the proximal electrode, the P2-scribe when filled with an electrical conductive material (typically the distal electrode), forms an electrical connection between distal and proximal electrodes and the P3-scribe to isolate regions of the distal electrode. The proximal electrode is most proximal to the light source or the light transmission layer of the module and the distal electrode is more distal from the light transmission layer. Also, the P4 scribe, which is not part of the interconnect, is a similar feature scribing through all the module layers to electronically isolate regions of the module from each other and run perpendicular to the interconnect scribes described above. While all of these scribes help to maximize the performance of the module they do expose the module to a few degradation mechanisms due to chemical reactions that occur upon laser ablation and over time as layers of the module that were not previously in contact now are and ingress/egress pathways throughout the module architecture are now present.

[0004] A brief description of each scribe of a typical thin film module interconnect, and notably with perovskite active layer, is as follows.

[0005] The P1-scribe ablates through only the proximal electrode to the substrate and is used to electrically isolate regions of the proximal electrode. Typically, this is the most robust, stable scribe.

[0006] The P2-scribe ablates through all the layers between the distal and proximal electrodes and is then filled in with the distal electrode forming a conductive path between sub-cells. This scribe is susceptible to chemical reaction degradation as the perovskite layer is in direct contact with the distal electrode that in some cases results in a reaction which typically produces a metal halide salt that is insulating and breaks the flow of current out of the module causing catastrophic performance loss.

[0007] The P3-scribe ablates the distal electrode down to the underlying module layers and is used to electrically isolate regions of the distal electrode. In theory this is the case, however, in practice the perovskite module layers are softer and much easier to ablate than the distal electrode and end up being ablated along with the distal electrode thus leaving a gap in the module down to the proximal electrode. As a result, this scribe is susceptible to chemical reaction with water vapor and oxygen, each of which is detrimental to module performance and provides a potential pathway for egress of valuable chemical species in the perovskite module.

[0008] The P4-scribe is a scribe that is not part of the official interconnect but is similar to them. This scribe ablates the entire module down to the substrate and requires full electrical isolation to differentiate regions of the module, which again leaves a gap in the module that exposes the module layers making them susceptible to chemical reaction with water vapor and oxygen, each of which is detrimental to module performance and also provides a potential pathway for egress of valuable chemical species from the perovskite layer of the module.

[0009] To form the interconnects, the layers of the module are ablated utilizing laser or knife-edge approaches at different stages in the module fabrication process. These interconnects thus result in an intermixing of module layers that normally would not be in contact (P2-scribe) or areas of the module where the architecture is fully 'uncapped' (P3 and P4-scribes). All features expose the module to significant degradation mechanisms that are problem in the multi sub-cell, commercial scale modules, however, these features are not present in smaller lab scale single-cell

devices that have a sandwich architecture (i.e. without interconnects). The latter is utilized for small scale device fabrication (1 cm<sup>2</sup> or less) and the target of a vast majority of research labs.

**[0010]** The P2-scribe forms a pathway between the distal electrode (often a metal layer) with the perovskite active layer for electrical contact. Through this direct contact the halide of the perovskite formulation can react with that distal electrode material forming a metal halide that is insulating, blocking electron transport through P2-scribe of the module. The impact of the formation of the electrically insulating material is catastrophic on module performance as optimal conductivity is required at the P2-scribe location to get the requisite charge out of the module.

**[0011]** Additional potential defects involve creation of unbonded, metallic Lead (Pb) upon laser ablation of the perovskite to form the P2-scribe. This metallic lead acts as a charge recombination center and if it migrates to the active area of the module will cause decreases in the module performance in both efficiency and stability. The halide in the X-site may also enter the vapor phase upon laser ablation of the perovskite that can result in halide vacancies in the crystal lattice that can easily migrate throughout the active layer causing instability and efficiency loss. Similarly to the halide the A-site element or molecule may end up vaporized in the process leading to vacancy defects in the lattice that can then migrate throughout the module resulting in performance issues. The elements, Cesium (Cs) or Rubidium (Rb), if present in the A-site may also end up in a metallic state and result in a charge recombination center. Furthermore, these elements can more easily migrate throughout the perovskite layer than the lead and could form metal clusters that would lead to significant efficiency and stability loss in the module.

**[0012]** A P3-scribe is an ablation or removal of the distal electrode material to isolate regions of the module in regard to that electrode, which is often accomplished through laser ablation. However, because the perovskite material and the charge transport layers are often easier to ablate than the distal electrode layer, they are typically ablated as well in the P3-scribe processing. As a result, this creates an air gap in the module that serves not only as an easy ingress pathway for water vapor and oxygen but also as an egress pathway for the A-site cation or the X-site halide of the perovskite layer. This air gap could potentially be filled in with the encapsulant material in the overall packaging of the module but having direct contact of the

laminate with the module layers can result in degradation mechanisms. For example, a common laminate, ethyl-vinyl-acetate (EVA), produces acetic acid as it degrades over the lifetime of a PV module and that can damage the perovskite or other layers of the module.

[0013] A P4-scribe extends through all the photovoltaic module layers to electrically isolate regions of the module. This presents the same issues and concerns as described for the P3-scribe.

#### SUMMARY OF THE INVENTION

[0014] The invention is directed to a photovoltaic module that has a plurality of sub-cells that are electrically connected by interconnects through a series of scribes and wherein one or more of the scribes includes a scribe barrier layer to prevent degradation mechanisms and in some cases a pre-treatment of the exposed perovskite layer to mitigate defects induces from the scribe processing, typically laser ablation. The series of scribes that form the interconnect are the P1-scribe, P2-scribe and P3-scribe. The result is a series of interconnected sub-cells which are separated from the adjacent series of sub-cells by a P4-scribe that extends orthogonally to the interconnect scribes. The combination of the P4-scribes on opposing sides of a series of interconnected sub-cells along with the interconnect scribes form the individual sub-cells of the module. Electrical current flows along adjacent sub-cells in a direction parallel with the P4-scribes to the sides of the module where it is picked up by the busbars.

[0015] A photovoltaic module has an exposed side, exposed to the sun or light for producing electricity, referred to herein as the proximal side, and a distal side, opposite the proximal side or distal from the incident light on the photovoltaic module. The photovoltaic module includes a number of layers arranged successively from the proximal side to distal side including a light transmission layer, such as glass, a proximal electrode layer, a proximal charge transport layer, a perovskite layer, a distal charge transport layer and a distal electrode layer. The term proximal as used herein means that that layer is more proximal to the proximal side of the photovoltaic module than the distal side.

[0016] The light transmission layer is usually a glass layer and typically low Iron content glass, solar grade, and in a module ranges from 2-6 mm thickness.

[0017] The proximal charge transport layer is used to extract holes or electrons and subsequently block electrons or holes from this side of the module depending on whether the architecture is (positive-intrinsic-negative) (PIN) or negative-intrinsic-positive (NIP), respectively.

[0018] The perovskite layer is the photoactive layer of the module and can be made by a variety of substituents resulting in the  $ABX_3$  crystal structure known as perovskite. The thickness of the perovskite layer in the module can vary from about 150 nm to about 1200 nm in thickness. In the photoactive forms the constituents of the lattice generally are: A-site is Cesium (Cs), Rubidium (Rb), Sodium (Na), Potassium (K) or a small organic molecule Methyl Ammonium, Formamidinium, Guanadinium; the B-site is Lead (Pb) or Tin (Sn); the X-site is a halide of Iodide (I), Bromide (Br) or Chloride (Cl). Depending on the formulation, the band gap can be tuned from about 1.2 eV to over 3.0 eV resulting in a variety of tunable absorbance spectrums to harness different region of the solar spectrum, making it ideally suited for tandem and multijunction applications. A perovskite layer may be configured with or on a silicon layer, which may be used for tandem and multi-junction photovoltaic modules.

[0019] The distal charge transport layer is used to extract holes or electrons and subsequently block electrons or holes from this side of the module depending on whether the architecture is (positive-intrinsic-negative) (PIN) or negative-intrinsic-positive (NIP), respectively.

[0020] Common materials used for the charge transport layers, distal or proximal, when extracting electrons, include, but are not limited to, organic materials such as fullerenes ( $C_{60}$ ), [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) at 10-40 nm thickness with a subsequent Bathocuporine (BCP) material at 2-10 nm thickness. Additional monolayers may be added such as lithium fluoride (LiF) or magnesium fluoride ( $MgF_2$ ) at a thickness of 0.1-3 nm. Additional use or as is use of a metal oxide is also possible such as tin oxide ( $SnO_2$ ) at 10-40 nm thickness.

[0021] Materials used for the charge transport layers, distal or proximal, when extracting holes, include, but are not limited to metal oxides such as Nickel Oxide (NiO) or organic materials from small molecules to polymers such as Poly [bis (4-

phenyl) (2,4,6-trimethylphenyl)amine (PTAA) at 5-40 nm in concert with (Poly (9,9-bis(3'-(N,N-dimethylamino)propyl)-2,7-fluorene)-alt-2,7-(9,9-dioctylfluorene) (PFN) as a monolayer ~0.5-3 nm thickness.

**[0022]** The distal electrode layer is commonly a metal, Silver (Ag), Copper (Cu), Aluminum (Al) or Gold (Au) in a monofacial module and has thicknesses of around 80-200 nm. In the case of a bifacial module this would also need to be a transparent conductive layer and may include indium tin oxide (ITO), fluorine doped tin oxide (FTO), indium zinc oxide (IZO), and is on the order of 100-500 nm thick depending on the material and how limited it is in conductivity.

**[0023]** An exemplary photovoltaic module has a plurality of scribes, P1-scribe, P2-scribe and P3-scribe forming an interconnect between sub-cells of the photovoltaic module. The P2 scribe barrier layer may be preferably an electrically conductive or insulating materials, as described herein, and the P3 scribe barrier layer and P4 scribe barrier layer are electrically non-conductive materials, as described herein.

**[0024]** The scribes and particularly the scribe sides, the opposing walls through one or more layers of the photovoltaic module, are susceptible to degradation from water vapor and oxygen exposure or chemical reactions between layers that are now in contact as a result of the scribe and subsequent scribe fill. A scribe barrier layer is configured to reduce or prevent these degradation mechanisms providing a more durable photovoltaic module. Furthermore, the scribes may be made thinner wherein a width between opposing scribe sides can be reduced because the scribe includes a scribe barrier layer extending along the scribe sides to prevent degradation that can lead to loss of electrical conduction through the scribe which diminishes performance of the photovoltaic module.

**[0025]** As described herein, the P2 scribe barrier layer may be electrically conductive as defined herein which may aid in conducting electrical current between the distal electrode and the proximal electrode. The P3 scribe barrier layer and P4 scribe barrier layer are electrically non-conductive, as defined herein.

**[0026]** The P1-scribe extends through the proximal electrode layer to the light transmission layer. This P1-scribe extends into or through the light transmission layer to electrically isolate regions of the bottom electrode from each other. The P1-scribe may be filled with the proximal charge transport layer material.

**[0027]** A P2-scribe extends through the proximal electrode layer, the proximal charge transport layer, the perovskite layer and the distal charge transport layer configured over the proximal electrode layer. The P2-scribe extends through the distal charge transport layer, the perovskite layer and the proximal hole or electron transport layer and to the proximal electrode layer. The P2-scribe forms the conductive connection between the sub-cells in the module once it is filled with an electrically conductive material, such as the distal electrode material. When the distal electrode is deposited, it may fill in the P2-scribe to form this electrical connector between the distal electrode and the proximal electrode. It is essential that this conduction path be present for the module to perform. A P2-scribe may be formed by laser ablation and may have a P2-scribe width of about 10-200 micrometers, or at least 10 micrometers at least 20 micrometers, at least 50 micrometers, at least 100 micrometers, at least 150 micrometers, at least 200 micrometers and any range between and including the width values provided. The width may be thinner when a conductive P2 scribe barrier layer is used.

**[0028]** A P2 scribe barrier layer may extend over the distal charge transport layer and down into the P2-scribe along the scribe-sides of the distal charge transport layer, perovskite layer, and proximal charge transport layer and to the proximal electrode layer and may be deposited through vapor deposition or by solution coating. The P2 scribe barrier layer may extend over the distal surface of the distal charge transport layer and will extend along the scribe-sides of the P2-scribe, running along the exposed edge of the distal charge transport layer, exposed edge of the perovskite layer, and the exposed edge of the proximal charge transport layer, and may or may not extend over the proximal electrode layer at the base of the P2-scribe. The P2 scribe barrier layer forms a continuous layer over the scribe sides and may form a continuous layer along the scribe sides and the scribe base to prevent water and moisture ingress into these layers and prevent chemical reactions between module layers, in particular the distal electrode with the perovskite layer.

**[0029]** An electrically conductive P2 scribe barrier layer may be a metal oxide such as indium zinc oxide (IZO). The P2 scribe barrier layer may include or consist of a other metal oxides selected from the group consisting of indium tin oxide (ITO), fluorinated tin oxide (FTO), molybdenum oxide (MoOx) and molybdenum sulfide (MoS<sub>2</sub>),

[0030] The P2 scribe barrier layer may include or consist of fullerenes (C<sub>60</sub>), [6,6]-phenyl-C61-butyric acid methyl ester (PCBM), or , organic molecules and polymers. A preferred material for the P2 scribe barrier layer is a fullerene such as C<sub>60</sub>. The P2 scribe barrier layer, when electrically conductive may have a thickness of about 2nm or more, about 5nm or more, about 10nm or more, about 15nm or more, about 20nm or less or from about 2nm to about 20nm and any other range between and including the thickness values provided.

[0031] The P2 scribe barrier layer may be electrically non-conductive having a surface resistivity at least  $1 \times 10^{12}$  ohm/sq and a volume resistivity of at least  $1 \times 10^{11}$  ohm-cm and may include a metal oxide such as silicon monoxide (SiO<sub>x</sub>). Other electrically non-conductive materials for the P2 scribe barrier layer may include or consist of a material selected from the group consisting of aluminum oxide (Al<sub>2</sub>O<sub>3</sub>), hafnium oxide (HfO<sub>2</sub>), zirconium dioxide (ZrO<sub>2</sub>), silicon nitride (Si<sub>3</sub>N<sub>4</sub>), and more generally, metal oxides, metal nitrides and metal carbides. Also, an electrically non-conductive P2 scribe barrier layer may be a polymeric material such as polystyrene, poly-methyl methacrylate (PMMA), acrylic or poly-carbonate. The P2 scribe barrier layer, when electrically non-conductive may have a thickness of no more than about 5nm, such as from about 1nm to about 5nm.

[0032] A P3-scribe may be formed by laser ablation and may have a P3-scribe width of about 10-200 micrometers, or at least 20 micrometers, at least 20 micrometers, at least 50 micrometers, at least 100 micrometers, at least 150 micrometers, at least 200 micrometers and any range between and including the width values provided. The width of the P3-scribe may be thinner than conventional P3-scribes when a P3 scribe barrier layer is incorporated and may be about 100 micrometers or less. The P3 scribe barrier layer may substantially to completely fill the P3-scribe, as defined as a cross-section of a P3-scribe having a porosity of no more than 10%.

[0033] A P3 scribe barrier layer may be a non-conductive material, or electrically insulating material, as defined herein, and may be deposited through vapor deposition or by solution coating. The P3 scribe barrier layer extends along the scribe sides of the P3-scribe, over the exposed edges of the distal electrode layer, exposed edges of the distal charge transport layer, exposed edges of the perovskite layer, exposed edges of the proximal charge transport layer down to the proximal electrode. A P3 scribe barrier layer may extend over the entire distal electrode

encapsulating the module and may comprise materials such as silicon monoxide ( $\text{SiO}_x$ ), aluminum oxide  $\text{Al}_2\text{O}_3$ , hafnium oxide ( $\text{HfO}_2$ ), zirconium oxide ( $\text{ZrO}_2$ ), silicon nitride ( $\text{Si}_3\text{N}_4$ ), and more broadly electrically insulating metal oxides, metal nitrides and metal carbides or a combination thereof. A P3 scribe barrier layer may comprise polystyrene, poly-methyl methacrylate (PMMA), acrylics, poly-carbonate and more generally electrically insulating organic materials (polymers or small molecules) and any nanoparticles of the afore mentioned materials or a combination thereof.

**[0034]** A P4-scribe extends through the distal electrode layer, distal charge transport layer, perovskite layer, proximal charge transport layer and proximal electrode layer, down to the light transmission layer, and the glass substrate. A P4 scribe barrier layer may extend over the distal electrode layer encapsulating the module. The P4 scribe barrier layer extends along the scribe sides of the P4-scribe, over the exposed edges of the distal electrode layer, exposed edges of the distal charge transport layer, exposed edges of the perovskite layer, exposed edges of the proximal charge transport layer and exposed edges of the proximal electrode layer, down to the light transmission layer. A P4 scribe barrier base extension may extend over the light transmission layer. The P4 scribe barrier layer forms a continuous layer over the scribe sides and may form a continuous layer from the scribe sides over the scribe base to prevent water and moisture ingress into these layers and prevent corrosion and potential egress of A-site and X-site substituents of the perovskite lattice. As described herein the P4 scribe barrier layer is an electrically insulating material.

**[0035]** A P4-scribe may be formed by laser ablation and may have a P4-scribe width of about 10-200 micrometers, or at least 10 micrometers, at least 20 micrometers, at least 50 micrometers, at least 100 micrometers, at least 150 micrometers, at least 200 micrometers and any range between and including the width values provided. The width of the P4-scribe may be thinner than conventional P4-scribes when a P4 scribe barrier layer is incorporated and may be about 100 micrometers or less. The P4 scribe barrier layer may substantially or completely fill the P4-scribe, as defined as a cross-section of a P4-scribe having a porosity of no more than 10%.

**[0036]** A P4 scribe barrier layer is a non-conductive material, or electrically insulating material, as defined herein, and may be deposited through vapor deposition or by solution coating. A P4 scribe barrier layer may comprise  $\text{SiO}_x$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{HfO}_2$ ,  $\text{ZrO}_2$ ,  $\text{Si}_3\text{N}_4$ , and more broadly insulating metal oxides, metal nitrides and metal carbides or

a combination thereof. A P4 scribe barrier layer also may be comprised of polystyrene, PMMA, acrylics, poly-carbonate, generally any insulating organic materials (polymers or small molecules) or nanoparticles of the above mentioned materials or a combination thereof. The materials listed here may be deposited through either vapor deposition or solution coating. The thickness of the P3 scribe barrier layer and P4 scribe barrier layer may be about 10nm or more, about 20nm or more, about 50nm or more, about 75nm or more, about 100nm or more, of from about 10nm to 1000nm, and as described herein may also extend from a first scribe side to an opposing scribe side and form a single layer therebetween.

**[0037]** While the material for the P2 scribe barrier layer is preferred to be electrically conductive, the material for the P3 and P4-scribes barrier layer needs to be electronically insulating. The P2 scribe barrier layer is designed to prevent direct contact between the distal electrode and perovskite layer, preventing a chemical reaction between those two layers degrading performance. The electrical conductivity of the P2-scribe layer enables the proper charge carrier extraction within the module.

**[0038]** The P3-scribe is electrically insulating to prohibit unwanted electrical connection across the series connected sub-cells and may prevent the ingress of humidity and oxygen and the egress of A-site or X-site materials from the perovskite layers. The P4-scribe may also prevent the ingress of humidity and oxygen and the egress of A-site or X-site materials from the perovskite layers.

**[0039]** The barrier layers may be applied through sputtering, or vapor deposition, or through coating, such as solution coating. Sputtering may be used for conductive oxides, such as Indium Tin Oxide (ITO), Fluorinated Tin Oxide (FTO), Indium Zinc Oxide (IZO) and the like.

**[0040]** The electrically insulating barrier layers for the P3-scribe and P4-scribe may be applied through thermal evaporation of materials, such as silicon monooxide ( $\text{SiO}_x$ ) and the like.

**[0041]** Polymeric barrier layers may be applied through coating, such as solution coating, wherein the polymer is dissolved into a solution and then coated and wherein the solvent is evaporated to leave the polymer. Polymers that may be solution coated include, but are not limited to polystyrene, Poly(methyl methacrylate) (PMMA) and the like.

[0042] A P3 scribe barrier layer extends along the scribe sides formed by the P3-scribe and wherein the P3 scribe barrier layer is electrically non-conductive having a surface resistivity at least  $1 \times 10^{12}$  ohm/sq and a volume resistivity of at least  $1 \times 10^{11}$  ohm-cm. A P4 scribe barrier layer extends along the scribe sides formed by the P4-scribe and wherein the P4 scribe barrier layer is electrically non-conductive having a surface resistivity at least  $1 \times 10^{12}$  ohm/sq and a volume resistivity of at least  $1 \times 10^{11}$  ohm-cm.

[0043] The P3 scribe barrier layer and/or the P4 scribe barrier layer may include or consist of a metal oxide, such as silicon monoxide (SiOx), a polymer, such as polystyrene and may have a thickness of at least 10nm, and may be 10nm or more, about 20nm or more about 30nm or more, about 40nm or more, about 50nm or more or about 100nm or from about 10nm to about 100nm. Also, the P3 scribe barrier layer and/or the P4 scribe barrier layer may extend across the scribe from a first scribe side to an opposing scribe side the respective scribe. The P3 scribe barrier layer and/or the P4 scribe barrier layer may substantially fill the respective P3-scribe, wherein a cross-section of the P3-scribe has a porosity of no more than 10%.

[0044] A primer may be applied to a scribe, such as a chelating agent or passivation layer, prior to application of the scribe barrier layer to mitigate the defects formed by the laser ablation for the formation of the scribe. The primer, chelating agent or passivation layer, may also improve contact of the scribe barrier layer with the layers along the scribe sides. The primer may be used primarily for defect mitigation in the perovskite layer, primarily along the scribed sides of the perovskite layer. Examples of chelating agents include Cuprous Thiocyanate (CuSCN) and more generally thiocyanate salts. Examples of passivation layer materials include, but are not limited to, the class of ammonium salts.

Definitions:

[0045] Electrically non-conductive scribe barrier layers are defined as having a surface resistivity of at least  $1 \times 10^{12}$  ohm/sq or a volume resistivity of at least  $1 \times 10^{11}$  ohm-cm. The term electrically insulating may be used interchangeably for electrically non-conductive, herein.

[0046] Conductive scribe barrier layers are defined as having a surface resistivity of no more than  $10^5$  ohm/sq or a volume resistivity no more than  $10^4$  ohm-cm.

[0047] It will be apparent to those skilled in the art that various modifications, combinations and variations can be made in the present invention without departing from the scope of the invention. Specific embodiments, features and elements described herein may be modified, and/or combined in any suitable manner. Thus, it is intended that the present invention cover the modifications, combinations and variations of this invention provided they come within the scope of the appended claims and their equivalents.

[0048] The summary of the invention is provided as a general introduction to some of the embodiments of the invention and is not intended to be limiting. Additional example embodiments including variations and alternative configurations of the invention are provided herein.

#### BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

[0049] The accompanying drawings are included to provide a further understanding of the invention and are incorporated in and constitute a part of this specification, illustrate embodiments of the invention, and together with the description serve to explain the principles of the invention.

[0050] Figure 1 shows a photovoltaic module having a plurality of sub-cells that are electrically connected in series by interconnects.

[0051] Figure 2 shows a cross-sectional view of a portion of a photovoltaic module having a plurality of scribes, P1, P2, and P3 forming an interconnect between sub-cells of the module.

[0052] Figure 3 shows a cross-sectional view of a portion of a photovoltaic module having a light transmission layer and a proximal electrode layer.

[0053] Figure 4 shows a cross-sectional view of the photovoltaic module shown in FIG. 3, with a P1-scribe in the proximal electrode layer.

[0054] Figure 5 shows a cross-sectional view of a portion of a photovoltaic module having the P1-scribe and a proximal charge transport layer, a perovskite layer and distal charge transport layer configured over the proximal electrode layer.

[0055] Figure 6 shows a cross-sectional view of the photovoltaic module shown in FIG. 5 with a P2-scribe extending through the distal charge transport layer, perovskite layer, and proximal charge transport layer to the proximal electrode layer.

[0056] Figure 7 shows a cross-sectional view of the photovoltaic module shown in FIG. 6 with a P2 scribe barrier layer extending over the distal charge transport layer and down into the P2-scribe along the scribe-sides of the distal charge transport layer, perovskite layer, and proximal charge transport layer and to the proximal electrode layer.

[0057] Figure 8 shows a cross-sectional view of the photovoltaic module shown in FIG. 7 with a distal electrode layer extending over the distal charge transport layer and over the P2 scribe barrier layer.

[0058] Figure 9 shows a cross-sectional view of the photovoltaic module shown in FIG. 8 with a P3-scribe extending through the distal electrode layer, as well as the distal charge transport layer, perovskite layer and proximal charge transport layer and to the proximal electrode layer.

[0059] Figure 10 shows a cross-sectional view of the photovoltaic module shown in FIG. 9 with a P3 scribe barrier layer extending over the distal electrode layer and down into the P3-scribe along the scribe-sides of the distal electrode layer, as well as the distal charge transport layer, perovskite layer and proximal charge transport layer and to the proximal electrode layer.

[0060] Figure 11 shows a cross-sectional view of the photovoltaic module shown in FIG. 10 with a P4-scribe extending through the distal electrode layer, distal charge transport layer, perovskite layer, proximal charge transport layer and proximal electrode layer, and down to the light transmission layer.

[0061] Figure 12 shows a cross-sectional view of the photovoltaic module shown in FIG. 11 with a P4 scribe barrier layer extending over the distal electrode layer and down along the scribe-sides of the distal electrode layer, distal charge transport layer, perovskite layer, proximal charge transport layer and proximal electrode layer, and down to the light transmission layer.

[0062] The figures represent an illustration of some of the embodiments of the present invention and are not to be construed as limiting the scope of the invention in any manner. Some of the figures may not show all of the features and components of the invention for ease of illustration, but it is to be understood that where possible, features and components from one figure may be included in the other figures. Further, the figures are not necessarily to scale, some features may be exaggerated to show details of particular components. Therefore, specific structural and functional

details disclosed herein are not to be interpreted as limiting, but merely as a representative basis for teaching one skilled in the art to variously employ the present invention.

#### DETAILED DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

**[0063]** As used herein, the terms "comprises," "comprising," "includes," "including," "has," "having" or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a process, method, article, or apparatus that comprises a list of elements is not necessarily limited to only those elements but may include other elements not expressly listed or inherent to such process, method, article, or apparatus. Also, use of "a" or "an" are employed to describe elements and components described herein. This is done merely for convenience and to give a general sense of the scope of the invention. This description should be read to include one or at least one and the singular also includes the plural unless it is obvious that it is meant otherwise.

**[0064]** Certain exemplary embodiments of the present invention are described herein and are illustrated in the accompanying figures. The embodiments described are only for purposes of illustrating the present invention and should not be interpreted as limiting the scope of the invention. Other embodiments of the invention, and certain modifications, combinations and improvements of the described embodiments, will occur to those skilled in the art and all such alternate embodiments, combinations, modifications, improvements are within the scope of the present invention.

**[0065]** As shown in FIG. 1, a photovoltaic module 10 has a plurality of sub-cells 12, 12', 12'' that are electrically connected by interconnects 16. Also, the P4-scribes 44, 44' extend orthogonally to the interconnect 16, 16' to form the sub-cells and to direct the current to flow to the sides of the module where it is picked up by the busbars 17, 17'. The current flows from sub-cell 12 to adjacent sub-cell 12' in a direction parallel with the P4-scribes.

**[0066]** As shown in FIG. 2, a photovoltaic module 10 has an exposed side, exposed to the sun 100 or light for producing electricity, referred to herein as the proximal side 11, and a distal side 15, opposite the proximal side or distal from the incident light on

the photovoltaic module. The photovoltaic module 10 includes a number of layers arranged successively from the proximal side 11 to distal side 15 including a light transmission layer 29, such as glass, a proximal electrode layer 28, a proximal charge transport layer 26, a perovskite layer 24, a distal charge transport layer 22 and a distal electrode layer 20.

**[0067]** The photovoltaic module 10 has a plurality of scribes, P1-scribe 41, P2-scribe 42, and P3-scribe 43 forming an interconnect between sub-cells 12, 12' of the photovoltaic module. The P2 scribe barrier layer 50 may be an electrically conductive material or layer, as described herein, and the P3 scribe barrier layer 60 and P4 scribe barrier layer 70 (shown in FIG. 12) are electrically insulating materials, as described herein.

**[0068]** The scribes and particularly the scribe sides, the opposing walls through one or more layers of the photovoltaic module are susceptible to degradation from water 18 and oxygen 19 exposure or chemical reactions between adjacent layers. A scribe barrier layer is configured to reduce or prevent these degradation mechanisms along the scribe sides to provide a more durable and efficient photovoltaic module and may be used in combination with or without a primer. Furthermore, when a scribe barrier layer is applied, the scribes may be made thinner wherein a width between opposing scribe sides can be reduced.

**[0069]** As described herein the P2 scribe barrier layer may be electrically conductive as defined herein which may aid in conducting electrical current between the distal electrode layer 20 and the proximal electrode layer 28. The P3 scribe barrier layer and P4 scribe barrier layer are electrically non-conductive as defined herein.

**[0070]** Referring now to FIGS. 3 and 4, a photovoltaic module 10 has a light transmission layer 29 and a proximal electrode layer 28 on the light transmission layer. In FIG. 4, a P1-scribe 41 extends through the proximal electrode layer 28, to the light transmission layer 29, forming scribe sides 46, 46', opposing sides along the scribe in the proximal electrode layer 28. This P1-scribe extends to the light transmission layer in order to electrically isolate regions of the bottom electrode from each other. The P1-scribe may be filled with the proximal charge transport layer material and other subsequently deposited layers of the module, as shown in FIG. 5. As shown in FIG. 5, the P1-scribe 41 is filled with the proximal charge transport layer

26. Also, in FIG. 5 the perovskite layer 24 and distal charge transport layer 22 are shown extending over the proximal charge transport layer 26.

**[0071]** Referring now to FIGS. 5 to 7, a photovoltaic module has the P1-scribe 41 through the proximal electrode layer 28, and a proximal charge transport layer 26, a perovskite layer 24 and distal charge transport layer 22 configured over the proximal electrode layer 28. As shown in FIG. 42, a P2-scribe 42 extends through the distal charge transport layer 22, perovskite layer 24, and proximal charge transport layer 26 and to the proximal electrode layer 28, forming scribe sides 56, 56', opposing sides of the P2-scribe in the distal charge transport layer 22, perovskite layer 24, and proximal charge transport layer 26. The P2-scribe forms the conductive pathway for the connection between the sub-cells in the module and is filled with an electrically conductive material, such as the distal electrode material. When the distal electrode is deposited, it may fill in the P2-scribe to form this electrical connector between the distal electrode layer 20 and the proximal electrode layer 28. It is essential that this conduction path be present for the module to perform. A P2-scribe may be formed by laser ablation and may have a P2-scribe width 55 of about 10-200 micrometers and may be thinner when a conductive P2 scribe barrier layer is used. A primer 82 may be applied to the P2-scribe, or along the scribe sides of the P2-scribe to mitigate defects from the formation of the P2-scribe, such as through laser ablation. This primer would be added prior to deposition of the P2 scribe barrier layer or the distal electrode.

**[0072]** As shown in FIG. 7, a P2 scribe barrier layer 50 extends over the distal charge transport layer 22 and down into the P2-scribe along the scribe-sides of the distal charge transport layer 22, perovskite layer 24, and proximal charge transport layer 26 and to the proximal electrode layer 28. The P2 scribe barrier layer 50 includes a P2 barrier distal electron extension 52 extending over the distal surface of the distal charge transport layer 22, P2 scribe barrier side extension 54 extending along the scribe-sides of the distal charge transport layer 22, perovskite layer 24, and proximal charge transport layer 26, and a P2 scribe barrier base extension 58 extending over the proximal electrode layer 28. The P2 scribe barrier layer 50 forms a continuous layer over the scribe sides, and may be continue scribe base to prevent chemical reactions between the distal electrode layer 20 once deposited and the

perovskite layer, and additionally would prevent water and moisture ingress into these layers and prevent corrosion.

**[0073]** Figure 8 shows a cross-sectional view of the photovoltaic module 10 shown in FIG. 7 with a distal electrode layer 20 extending over the distal charge transport layer 22 and over the P2 scribe barrier layer 50.

**[0074]** The P2 scribe barrier layer may not have a P2 scribe barrier base extension 58, thereby enabling direct contact of the distal electrode to contact the proximal electrode upon deposition of the distal electrode layer 20.

**[0075]** Referring now to FIGS. 9 and 10, the photovoltaic module shown in FIG. 8 is now configured with a P3-scribe 43 extending through the distal electrode layer 20, as well as the distal charge transport layer 22, perovskite layer 24 and proximal charge transport layer 26 and to the proximal electrode layer 28. The P3-scribe forms scribe sides 66, 66', opposing sides of the P3-scribe in the distal electrode layer 20, distal charge transport layer 22, perovskite layer 24, and proximal charge transport layer 26. A primer 83 may be applied to the P3-scribe, or along the scribe sides of the P3-scribe to mitigate defects from the formation of the P3-scribe, such as through laser ablation.

**[0076]** As shown in FIG. 10, a P3 scribe barrier layer extends over the distal electrode layer 20 and down into the P3-scribe 43 along the scribe-sides of the distal electrode layer 20, as well as the distal charge transport layer 22, perovskite layer 24 and proximal charge transport layer 26 and to the proximal electrode layer 28. The P3 scribe barrier layer 60 includes a P3 barrier distal electrode extension 62 extending over the distal surface of the distal electrode layer 20, P3 scribe barrier side extensions 64 extending along the scribe-sides of the distal electrode layer 20, distal charge transport layer 22, perovskite layer 24, and proximal charge transport layer 26, and a P3 scribe barrier base extension 68 extending over the proximal electrode layer 28. The P3 scribe barrier layer 60 forms a continuous layer over the scribe sides and the scribe base to prevent water and moisture ingress into these layers and prevent corrosion, along with prevention of egress of material out of the perovskite layer. As described herein the P3 scribe barrier layer 60 may be an electrically non-conductive material and may have a thickness along the scribe sides 66, 66' or may substantially fill the P3-scribe wherein there is less than 10% porosity in the P4-scribe taken along a cross-section of the P3-scribe. A P3-scribe may be

formed by laser ablation and may have a P3-scribe width 65 shown in FIG. 9, of about 10-200 micrometers and may be thinner, such as about 100 micrometers or less when the P3 scribe barrier layer is thick or substantially fills the P3-scribe, as defined herein.

[0077] Referring now to FIGS. 11 and 12, the photovoltaic module shown in FIG. 10 is now configured with a P4-scribe 44 extending through the distal electrode layer 20, distal charge transport layer 22, perovskite layer 24, proximal charge transport layer 26 and proximal electrode layer 28, and down to the light transmission layer 29. The P4-scribe forms scribe sides 76, 76', opposing sides of the P4-scribe in the distal electrode layer 20, distal charge transport layer 22, perovskite layer 24, proximal charge transport layer 26 and the proximal electrode layer 28. A primer 84 may be applied to the P4-scribe, or along the scribe sides of the P4-scribe to mitigate defects from the formation of the P4-scribe, such as through laser ablation.

[0078] As shown in FIG. 12, a P4 scribe barrier layer 70 extends over the distal electrode layer 20 and down into the P4-scribe 44 along the scribe-sides of the distal electrode layer 20, distal charge transport layer 22, perovskite layer 24, proximal charge transport layer 26 and proximal electrode layer 28, and down to the light transmission layer 29. The P4 scribe barrier layer 70 includes a P4 barrier distal electrode extension 72 extending over the distal surface of the distal electrode layer 20, P3 scribe barrier side extensions 74 extending along the scribe-sides of the distal electrode layer 20, distal charge transport layer 22, perovskite layer 24, proximal charge transport layer 26 and proximal electrode layer 28, and a P4 scribe barrier base extension 78 extending over the light transmission layer 29. The P4 scribe barrier layer 70 forms a continuous layer over the scribe sides, the scribe base to prevent water and moisture ingress into these layers and prevent corrosion. As described herein, the P4 scribe barrier layer 70 is an electrically insulating material and may have a thickness along the scribe sides 76, 76' or may substantially fill the P4-scribe wherein there is less than 10% porosity in the P4-scribe taken along a cross-section of the P4-scribe. A P4-scribe may be formed by laser ablation and may have a P4-scribe width 75 of about 10-200 micrometers and may be thinner, such as about 100 micrometers or less when the P4 scribe barrier layer is thick or substantially fills the P4-scribe, as defined herein.

[0079] As shown in FIG. 12, a lamination layer 90 extends over the distal electrode layer 20 and may be a polymeric coating. The P4 scribe barrier layer may preferably be a material that is different from the lamination layer material 91 which may be ethyl-vinyl-acetate, a polyolefin or an ionomer and may fill in the entirety of any void present in P4 scribe as needed. Note that the lamination layer may fill in the scribe between the scribe sides and between the P4 scribe barrier layers on these scribe sides.

[0080] Note that the scribe barrier layers may extend along the scribe barrier base extension but this extension may not be required and may not be included. A scribe barrier layer may therefore extend along the scribe sides and may extend along the exposed top layer of the scribe.

[0081] It will be apparent to those skilled in the art that various modifications, combinations and variations can be made in the present invention without departing from the scope of the invention. Specific embodiments, features and elements described herein may be modified, and/or combined in any suitable manner. Thus, it is intended that the present invention cover the modifications, combinations and variations of this invention provided they come within the scope of the appended claims and their equivalents.

What is claimed is:

1. A photovoltaic module comprising sub-cells and an interconnect between said sub-cells, said photovoltaic module comprising:
  - a) a light transmission layer;
  - b) a proximal electrode layer;
  - c) a proximal charge transport layer;
  - d) a perovskite layer;
  - e) a distal charge transport layer; and
  - f) a distal electrode layer;wherein the perovskite layer is configured between the distal charge transport layer and proximal charge transport layer;  
wherein the interconnect comprises:
  - a) a P1-scribe extending into and forming scribe sides along the proximal electrode layer;
  - b) a P2-scribe extending into and forming scribe sides along the distal charge transport layer, the perovskite layer and into the proximal charge transport layer;
  - c) a P3-scribe extending into and forming scribe sides along the distal electrode layer, the distal charge transport layer, the perovskite layer and the proximal charge transport layer;
  - d) a P4-scribe extending into and forming scribe sides along the distal electrode layer, the distal charge transport layer, the perovskite layer, the proximal charge transport layer and the proximal electrode layer; and
  - e) a scribe barrier layer extending along the scribe sides formed by at least one of the P2-scribe, P3-scribe and P4-scribe.
2. The photovoltaic module of claim 1, wherein the scribe barrier layer is a P2 scribe barrier layer that extends along the scribe sides formed by the P2-scribe.
3. The photovoltaic module of claim 2, wherein the P2 scribe barrier layer is electrically conductive having a surface resistivity of no more than  $10^5$  ohm/sq and a volume resistivity no more  $10^4$  ohm-cm.
4. The photovoltaic module of claim 3, wherein the P2 scribe barrier layer comprises a metal oxide.

5. The photovoltaic module of claim 4, wherein the metal oxide is indium zinc oxide (IZO).
6. The photovoltaic module of claim 3, wherein the P2 scribe barrier layer consists of a material selected from the group consisting of indium tin oxide (ITO), fluorinated tin oxide (FTO), molybdenum oxide (MoO<sub>x</sub>) or molybdenum sulfide (MoS<sub>2</sub>).
7. The photovoltaic module of claim 3, wherein the P2 scribe barrier layer consists of a material selected from the group consisting of fullerenes (C<sub>60</sub>), [6,6]-phenyl-C61-butyric acid methyl ester (PCBM), organic molecules and polymers.
8. The photovoltaic module of claim 3, wherein the P2 scribe barrier layer has a thickness of between 2nm and 20nm.
9. The photovoltaic module of claim 2, wherein the P2 scribe barrier layer is electrically non-conductive having a surface resistivity at least  $1 \times 10^{12}$  ohm/sq and a volume resistivity of at least  $1 \times 10^{11}$  ohm-cm.
10. The photovoltaic module of claim 9, wherein the P2 scribe barrier layer comprises a metal oxide.
11. The photovoltaic module of claim 9, wherein the metal oxide is silicon monoxide (SiO<sub>x</sub>).
12. The photovoltaic module of claim 9, wherein the P2 scribe barrier layer consists of a material selected from the group consisting of silicon monoxide (SiO<sub>x</sub>), aluminum oxide (Al<sub>2</sub>O<sub>3</sub>), hafnium (HfO<sub>2</sub>), zirconium dioxide (ZrO<sub>2</sub>), silicon nitride (Si<sub>3</sub>N<sub>4</sub>), metal oxides, metal nitrides and metal carbides.
13. The photovoltaic module of claim 9, wherein the P2 scribe barrier layer comprises a polymeric material.
14. The photovoltaic module of claim 13, wherein the polymeric material is polystyrene.
15. The photovoltaic module of claim 9, wherein the P2 scribe barrier layer consists of a material selected from the group consisting of poly-methyl methacrylate (PMMA), acrylic and poly-carbonate.
16. The photovoltaic module of claim 9, wherein the P2 scribe barrier layer has a thickness of no more than 5nm.
17. The photovoltaic module of claim 2, wherein the P2-scribe further comprises a P2 primer between the scribe sides and the scribe barrier layer of the P2-scribe.

18. The photovoltaic module of claim 17, wherein the P2 primer comprises a chelating agent.
19. The photovoltaic module of claim 17, wherein the chelating agent comprises a thiocyanate salt.
20. The photovoltaic module of claim 17, wherein the chelating agent Cuprous Thiocyanate (CuSCN).
21. The photovoltaic module of claim 17, wherein the P2 primer is a passivation layer.
22. The photovoltaic module of claim 21, wherein the passivation layer comprises ammonium salt.
23. The photovoltaic module of claim 2, further comprising a P3 scribe barrier layer that extends along the scribe sides formed by the P3-scribe and wherein the P3 scribe barrier layer is electrically non-conductive having a surface resistivity at least  $1 \times 10^{12}$  ohm/sq and a volume resistivity of at least  $1 \times 10^{11}$  ohm-cm.
24. The photovoltaic module of claim 23, wherein the P3 scribe barrier layer comprises a metal oxide.
25. The photovoltaic module of claim 24, wherein the metal oxide comprises silicon monoxide ( $\text{SiO}_x$ ).
26. The photovoltaic module of claim 23, wherein the P3 scribe barrier layer comprises a polymer.
27. The photovoltaic module of claim 26, wherein the polymer comprises polystyrene.
28. The photovoltaic module of claim 23, wherein the P3 scribe barrier layer has a thickness of at least 10nm.
29. The photovoltaic module of claim 23, wherein P3 scribe barrier layer substantially fills the respective P3-scribe, wherein a cross-section of the P3-scribe has a porosity of no more than 10%.
30. The photovoltaic module of claim 23, wherein the scribe sides of the P3-scribe includes a first scribe side and an opposing second scribe side, and wherein the P3 scribe barrier layer extends across the P3-scribe from said first scribe side to said opposing scribe side of the P3-scribe.
31. The photovoltaic module of claim 23, wherein the P3-scribe further comprises a P3 primer between the scribe sides and the scribe barrier layer of the P3-scribe.

32. The photovoltaic module of claim 31, wherein the P3 primer comprises a chelating agent.
33. The photovoltaic module of claim 32, wherein the chelating agent comprises a thiocyanate salt.
34. The photovoltaic module of claim 32, wherein the chelating agent Cuprous Thiocyanate (CuSCN).
35. The photovoltaic module of claim 31, wherein the P3 primer is a passivation layer.
36. The photovoltaic module of claim 35, wherein the passivation layer comprises ammonium salt.
37. The photovoltaic module of claim 23, further comprising a P4 scribe barrier layer that extends along the scribe sides formed by the P4-scribe, and wherein the P4 scribe barrier layer is electrically non-conductive having a surface resistivity at least  $1 \times 10^{12}$  ohm/sq and a volume resistivity of at least  $1 \times 10^{11}$  ohm-cm.
38. The photovoltaic module of claim 37, wherein the P4 scribe barrier layer comprises a metal oxide.
39. The photovoltaic module of claim 38, wherein the metal oxide comprises silicon monoxide ( $\text{SiO}_x$ ).
40. The photovoltaic module of claim 37, wherein the P4 scribe barrier layer comprises a polymer.
41. The photovoltaic module of claim 40, wherein the polymer comprises polystyrene.
42. The photovoltaic module of claim 37, wherein the P4 scribe barrier layer has a thickness of at least 10nm.
43. The photovoltaic module of claim 37, wherein the P4 scribe barrier layer substantially fills the respective P4-scribe, wherein a cross-section of the P4-scribe has a porosity of no more than 10%.
44. The photovoltaic module of claim 37, wherein the scribe sides of the P4-scribe includes a first scribe side and an opposing second scribe side, and wherein the P4 scribe barrier layer extends across the P4-scribe from said first scribe side to said opposing scribe side of the P4-scribe.
45. The photovoltaic module of claim 44, wherein the scribe sides of the P3-scribe includes a first scribe side and an opposing second scribe side, and wherein the

- P3 scribe barrier layer extends across the P3-scribe from said first scribe side to said opposing scribe side of the P3-scribe.
46. The photovoltaic module of claim 37, wherein both the P3 scribe barrier layer and the P4 scribe barrier layer substantially fill the respective P3-scribe and P4-scribe, wherein a cross-section of the P3-scribe and the P4-scribe has a porosity of no more than 10%.
47. The photovoltaic module of claim 37, wherein the P4-scribe further comprising a P4 primer between the scribe sides and the scribe barrier layer of the P4-scribe.
48. The photovoltaic module of claim 47, wherein the P4 primer comprises a chelating agent.
49. The photovoltaic module of claim 48, wherein the chelating agent comprises a thiocyanate salt.
50. The photovoltaic module of claim 48, wherein the chelating agent Cuprous Thiocyanate (CuSCN).
51. The photovoltaic module of claim 47, wherein the P4 primer is a passivation layer.
52. The photovoltaic module of claim 51, wherein the passivation layer comprises ammonium salt.
53. The photovoltaic module of claim 1, wherein the scribe barrier layer is a P3 scribe barrier layer that extends along the scribe sides formed by the P3-scribe.
54. The photovoltaic module of claim 53, wherein the P3 scribe barrier layer is electrically non-conductive having a surface resistivity at least  $1 \times 10^{12}$  ohm/sq and a volume resistivity of at least  $1 \times 10^{11}$  ohm-cm.
55. The photovoltaic module of claim 54, wherein the P3 scribe barrier layer comprises a metal oxide.
56. The photovoltaic module of claim 55, wherein the metal oxide comprises silicon monoxide (SiO<sub>x</sub>).
57. The photovoltaic module of claim 54, wherein the P3 scribe barrier layer comprises a polymer.
58. The photovoltaic module of claim 57, wherein the polymer comprises polystyrene.
59. The photovoltaic module of claim 54, wherein the P3 scribe barrier layer has a thickness of at least 10nm.

60. The photovoltaic module of claim 54, wherein P3 scribe barrier layer substantially fills the respective P3-scribe, wherein a cross-section of the P3-scribe has a porosity of no more than 10%.
61. The photovoltaic module of claim 54, wherein the scribe sides of the P3-scribe includes a first scribe side and an opposing second scribe side, and wherein the P4 scribe barrier layer extends across the P3-scribe from said first scribe side to said opposing scribe side of the P3-scribe.
62. The photovoltaic module of claim 54, wherein the P3-scribe further comprises a P3 primer between the scribe sides and the scribe barrier layer of the P3-scribe.
63. The photovoltaic module of claim 62, wherein the P3 primer comprises a chelating agent.
64. The photovoltaic module of claim 63, wherein the chelating agent comprises a thiocyanate salt.
65. The photovoltaic module of claim 63, wherein the chelating agent Cuprous Thiocyanate (CuSCN).
66. The photovoltaic module of claim 62, wherein the P3 primer is a passivation layer.
67. The photovoltaic module of claim 66, wherein the passivation layer comprises ammonium salt.
68. The photovoltaic module of claim 53, further comprising a P4 scribe barrier layer that extends along the scribe sides formed by the P4-scribe, and wherein the P4 scribe barrier layer is electrically non-conductive having a surface resistivity at least  $1 \times 10^{12}$  ohm/sq and a volume resistivity of at least  $1 \times 10^{11}$  ohm-cm.
69. The photovoltaic module of claim 68, wherein the P3 scribe barrier layer comprises a metal oxide.
70. The photovoltaic module of claim 69, wherein the metal oxide comprises silicon monoxide ( $\text{SiO}_x$ ).
71. The photovoltaic module of claim 68, wherein the P4 scribe barrier layer comprises a polymer.
72. The photovoltaic module of claim 71, wherein the polymer comprises polystyrene.
73. The photovoltaic module of claim 68, wherein the P4 scribe barrier layer has a thickness of at least 10nm.

74. The photovoltaic module of claim 68, wherein the P4 scribe barrier layer substantially fills the respective P4-scribe, wherein a cross-section of the P4-scribe has a porosity of no more than 10%.
75. The photovoltaic module of claim 68, wherein the scribe sides of the P4-scribe includes a first scribe side and an opposing second scribe side, and wherein the P4 scribe barrier layer extends across the P4-scribe from said first scribe side to said opposing scribe side of the P4-scribe.
76. The photovoltaic module of claim 75, wherein the scribe sides of the P3-scribe includes a first scribe side and an opposing second scribe side, and wherein the P4 scribe barrier layer extends across the P3-scribe from said first scribe side to said opposing scribe side of the P3-scribe.
77. The photovoltaic module of claim 68, wherein both the P3 scribe barrier layer and the P4 scribe barrier layer substantially fills the respective P3-scribe and P4-scribe, wherein a cross-section of the P3-scribe and the P4-scribe has a porosity of no more than 10%.
78. The photovoltaic module of claim 68, wherein the P4-scribe further comprises a P4 primer between the scribe sides and the scribe barrier layer of the P4-scribe.
79. The photovoltaic module of claim 78, wherein the P4primer comprises a chelating agent.
80. The photovoltaic module of claim 79, wherein the chelating agent comprises a thiocyanate salt.
81. The photovoltaic module of claim 79, wherein the chelating agent Cuprous Thiocyanate (CuSCN).
82. The photovoltaic module of claim 78, wherein the P4 primer is a passivation layer.
83. The photovoltaic module of claim 82, wherein the passivation layer comprises ammonium salt.
84. The photovoltaic module of claim 1, wherein the scribe barrier layer is a P4 scribe barrier layer that extends along the scribe sides formed by the P4-scribe, and wherein the P4 scribe barrier layer is electrically non-conductive having a surface resistivity at least  $1 \times 10^{12}$  ohm/sq and a volume resistivity of at least  $1 \times 10^{11}$  ohm-cm.

85. The photovoltaic module of claim 84, wherein the P4 scribe barrier layer comprises a metal oxide.
86. The photovoltaic module of claim 85, wherein the metal oxide comprises silicon monoxide ( $\text{SiO}_x$ ).
87. The photovoltaic module of claim 84, wherein the P4 scribe barrier layer comprises a polymer.
88. The photovoltaic module of claim 87, wherein the polymer comprises polystyrene.
89. The photovoltaic module of claim 84, wherein the P4 scribe barrier layer has a thickness of at least 10nm.
90. The photovoltaic module of claim 84, wherein the P4 scribe barrier layer substantially fills the respective P4-scribe, wherein a cross-section of the P3-scribe has a porosity of no more than 10%.
91. The photovoltaic module of claim 84, wherein the scribe sides of the P4-scribe includes a first scribe side and an opposing second scribe side, and wherein the P4 scribe barrier layer extends across the P4-scribe from said first scribe side to said opposing scribe side of the P4-scribe.
92. The photovoltaic module of claim 84, wherein the P4-scribe further comprises a P4 primer between the scribe sides and the scribe barrier layer of the P4-scribe.
93. The photovoltaic module of claim 92, wherein the P4 primer comprises a chelating agent.
94. The photovoltaic module of claim 93, wherein the chelating agent comprises a thiocyanate salt.
95. The photovoltaic module of claim 93, wherein the chelating agent Cuprous Thiocyanate ( $\text{CuSCN}$ ).
96. The photovoltaic module of claim 92, wherein the P4 primer is a passivation layer.
97. The photovoltaic module of claim 96, wherein the passivation layer comprises ammonium salt.