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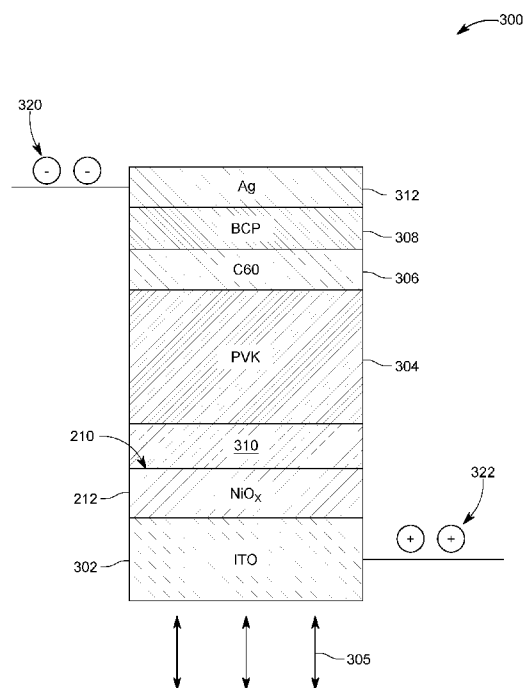


FIG. 3

(57) Abstract: A semiconductor device (300, 900, 950, 1000, 1050, 1200, 1250) includes a first electrode (302), a metal oxide layer (212) formed over the first electrode (302), a passivation layer (310) formed over a surface (210) of the metal oxide layer (212), an active layer (304) configured to transform light (305) into electrical charges (320, 322) or to transform electrical charges (320, 322) into the light (305), and a second electrode (312) formed over the active layer (304) and configured to channel the electrical charges (320, 322). The passivation layer (310) includes a metal-organic complex (400).

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PASSIVATION OF METAL OXIDE SURFACE WITH METAL-ORGANIC COMPLEX

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 63/117,118, filed on November 23, 2020, entitled "PASSIVATION OF METAL OXIDE SURFACE WITH METAL-ORGANIC COMPLEX," the disclosure of which is incorporated herein by reference in its entirety.

BACKGROUND

TECHNICAL FIELD

[0002] Embodiments of the subject matter disclosed herein generally relate to a system and method for passivating a metal oxide surface, and more particularly, to the passivation of metal oxide surfaces with metal-organic complexes for semiconductor and electronic devices.

DISCUSSION OF THE BACKGROUND

[0003] Metal oxides are a large class of materials incorporating binary or complex oxides with one or more metallic elements. They have been applied in photovoltaic and semiconductor technologies for many years. The remarkable versatility of their properties and the feasibility to be fabricated by simple, low-cost, and scalable fabrication methods confer to the metal oxides a unique place in

commercial as well as next-generation electronic and semiconductor industries. Specifically, these materials are chemically stable, not harmful for the environment, abundant in nature, and low cost.

[0004] However, the metal oxides have defects on their surfaces, originating from their under-coordinated surface atoms. The surface defects of the metal oxides increase their reactivity or catalytic activity, which is highly desirable for catalysis applications. On the other hand, the same surface defects induce in-gap states which act as detrimental interfaces when these materials are used in electronic devices. More specifically, the large number of grain boundaries in the thin metal oxide films limits the mobility of the carriers, thus reducing their concentration. These undesirable electronic states hamper the collection or transfer of charges (electrons and holes), and consequently, can reduce the efficacy of metal oxides in electronic and semiconductor applications. Hence, surface passivation of metal oxides is generally required to attain better performing devices.

[0005] However, the existing metal oxide passivation methods have one or more of the following shortcomings: there is not possible to passivate any metal oxide surface, it is not possible or is very difficult to tune the energy levels of the semiconducting metal oxides for specific applications, it is not possible to tune the passivation to obtain a hydrophobic surface or a hydrophilic surface, and it is difficult to form atomically thin passivation layers.

[0006] Thus, there is a need for a new passivation method and new passivation materials that can be easily controlled when applied to a metal-oxide

semiconductor device, to overcome one or more of the limitations of the existing methods discussed above.

BRIEF SUMMARY OF THE INVENTION

[0007] According to an embodiment, there is a semiconductor device that includes a first electrode, a metal oxide layer formed over the first electrode, a passivation layer formed over a surface of the metal oxide layer, an active layer configured to transform light into electrical charges or to transform electrical charges into the light, and a second electrode formed over the active layer and configured to channel the electrical charges. The passivation layer includes a metal-organic complex.

[0008] According to another embodiment, there is a semiconductor device that includes a substrate that includes a metal oxide material, a passivation layer formed directly over a surface of the substrate, an active layer configured to respond to a change in an external parameter, a first electrode formed over a first part of the substrate, and a second electrode formed over a second part of the substrate. The passivation layer includes a metal-organic complex.

[0009] According to yet another embodiment, there is a method for making a semiconductor device and the method includes a step of forming a first electrode, a step of depositing a metal oxide layer over the first electrode, a step of forming a passivation layer directly over a surface of the metal oxide layer, a step of forming an active layer over the passivation layer, where the active layer is configured to transform light into electrical charges or to transform electrical charges into the light, and a step of forming a second electrode over the active layer, where the second electrode is configured to channel the electrical charges. The passivation layer includes a metal-organic complex.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] For a more complete understanding of the present invention, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[0011] Figure 1 is a schematic diagram of the possible structures of a metal-organic complex that is used to passivate a metal-oxide layer;

[0012] Figure 2 schematically illustrates the chemical bonds between the metal-organic complex and the metal oxide layer;

[0013] Figure 3 illustrates a structure of a semiconductor device that has a metal oxide layer passivated with a metal-organic complex;

[0014] Figures 4A to 4F illustrate various metal-organic complexes that can be used to passivate a metal oxide layer;

[0015] Figures 5 to 8 compare various parameters (1) of a semiconductor device having the metal oxide layer passivated with a metal-organic complex relative to (2) a traditional semiconductor device that has no passivation layer;

[0016] Figures 9A and 9B illustrate solar cells having one or more metal oxide layers passivated with a metal-organic complex;

[0017] Figures 10A and 10B illustrate light emitting diodes having one or more metal oxide layers passivated with a metal-organic complex;

[0018] Figures 11A to 11E illustrate metal oxide transistors having one or more metal oxide layers passivated with a metal-organic complex;

[0019] Figures 12A and 12B illustrate photo-detectors having one or more metal oxide layers passivated with a metal-organic complex;

[0020] Figure 13 illustrates a sensor having one or more metal oxide layers passivated with a metal-organic complex; and

[0021] Figure 14 is a flow chart of a method for making one of the semiconductor devices discussed herein.

DETAILED DESCRIPTION OF THE INVENTION

[0022] The following description of the embodiments refers to the accompanying drawings. The same reference numbers in different drawings identify the same or similar elements. The following detailed description does not limit the invention. Instead, the scope of the invention is defined by the appended claims. The following embodiments are discussed, for simplicity, with regard to a semiconductor device having a single metal oxide layer passivated with a metal-organic complex. However, the embodiments to be discussed next are not limited to such a semiconductor device, but may be applied to other semiconductor devices that have plural metal oxide layers, and each such layer is passivated with a corresponding metal-organic complex.

[0023] Reference throughout the specification to “one embodiment” or “an embodiment” means that a particular feature, structure or characteristic described in connection with an embodiment is included in at least one embodiment of the subject matter disclosed. Thus, the appearance of the phrases “in one embodiment” or “in an embodiment” in various places throughout the specification is not necessarily referring to the same embodiment. Further, the particular features, structures or characteristics may be combined in any suitable manner in one or more embodiments.

[0024] According to an embodiment, a device having at least one metal oxide layer has the surface of this layer passivated with one or more metal-organic complexes and the passivated device can be tuned, by selecting the metal-organic

complex, for being used for specific electronic and/or semiconductor applications. The role played by the metal-organic complex can be tuned by selecting the metal, or the organic part of the metal-organic complex as now discussed.

[0025] As shown in Figure 1, organic ligands 110 coordinate or attach to a metal center atom 120 to form a metal-organic complex 100. Figure 1 shows 8 different metal-organic complexes 100. It is noted that each complex has a different number of organic ligands 110. The number of organic ligands 110 that connect to a same metal center atom 120 is called a coordination number CN. Different coordination modes are feasible, depending on the coordination number of the metal atom. The coordination number CN, also called ligancy, of a central metal atom 120 in a molecule 100 is the number of atoms, molecules or ions 110 bonded to it. The ion/molecule/atom 110 surrounding the central metal atom 120 is called a ligand.

[0026] For the case of metal-organic complexes 100, the organic ligands 110 can coordinate to the metal atom 120 via carbon, nitrogen, oxygen, sulfur, phosphorus, or halide atoms 112. This is schematically illustrated in Figure 2. The organic ligands 110 might have an ancillary or reactive character. Also, at least one ligand 110 may contain a functional group 130 or a combination of functional groups 130, as also illustrated in Figure 2. The functional group 130 may include one or more of carboxylic acid, phosphonic acid, carboxylate, cyanide, alcohol, ester, ketone, amine, amide, ether, thiocyanate, aldehyde, sulfide, sulfonic acid, sulfone and heterocycle (N, S, O) groups. The functional groups 130 allow attachment of the metal-organic complex 100 to a metal oxide surface 210, of a semiconductor device 200, which results in the passivation of the surface of the metal oxide surface 210.

Note that Figure 2 shows the semiconductor device 200 having at least a top metal oxide layer 212, that has the surface 210, and one or more other layers 220, which are discussed later. The number and type of the other layers 220 depends on the specific device that needs to be passivated, i.e., solar cell, light emitting diode, transistor, photo-detector, sensor, etc.

[0027] To enable the surface passivation of the semiconductor device 200, in one embodiment, the metal-organic complexes 100 are first dissolved in a solvent, such as water, methanol, ethanol, 1-propanol, iso-propanol, 1-butanol, sec-butanol, iso-butanol, tert-butanol, dimethylformamide, dimethyl sulfoxide, acetone, chlorobenzene, benzene, toluene, ethyl acetate, ethylene glycol, or a mixture of these solvents. Then, the resultant metal-organic complex solutions are coated onto the metal oxide surface 210 using solution deposition techniques such as spin-coating, blade coating, slot-die coating, dip-coating, web-coating, inkjet printing and/or spray deposition. After the deposition, an annealing process (up to 200 °C) may be necessary to enable successful binding of the metal-organic complex onto metal oxide surface. A thickness of the metal-organic complex added to the metal oxide surface can be controlled to vary between a monolayer to about 20 nm.

[0028] The metal oxide surface passivated device 200 shown schematically in Figure 2 is now discussed in more detail with regard to a specific metal oxide layer. The metal oxide layer is nickel oxide (NiO_x) and its surface defects were effectively passivated with ruthenium-based metal-organic complexes. More specifically, a p-i-n perovskite solar cell 300 is shown in Figure 3 as having the NiO_x layer 212 formed on top of an indium-tin-oxide (ITO) electrode 302. The ITO electrode 302 acts as a

conducting surface layer and also as an antireflective layer. The NiO_x layer 212 acts as a hole transport layer. The surface 210 of the NiO_x hole-transport layer 212, which is used to extract holes in the p-i-n perovskite solar cell 300, is passivated with a passivation layer 310, which includes a ruthenium-based dye 400, i.e., the metal-organic complex 100.

[0029] Plural ruthenium-based metal-organic complexes 400 have been tried by the inventors and the chemical structure and compositions of these complexes (N3 (C₂₆H₁₆N₆O₈RuS₂), N719 (C₅₈H₈₆N₈O₈RuS₂), C106 (C₄₄H₄₄N₆O₄RuS₆), K19 (C₅₂H₅₂N₆O₆RuS₂), Z907 (C₄₂H₅₆N₆O₄RuS₂), and N749 (C₆₉H₁₁₇N₉O₆RuS₃)) are illustrated in Figures 4A to 4F. All of the metal-organic complexes shown in these figures can coordinate with the NiO_x surface 210 and passivate the surface defects. In one embodiment, non-ruthenium-based metal-organic complexes 400 can be used for the passivation layer 310.

[0030] The solar cell 300 also includes a perovskite layer 304 formed directly over the passivation layer 212. The perovskite layer 304 is used to receive light 305 and transform it into electrical charges 320 and 322 (e.g., electrons and holes, respectively). The solar cell may further include a thin fullerene (C₆₀) layer 306 formed over the perovskite layer, and the fullerene layer 306 is used to extract electrons from the perovskite layer 304. The solar cell also includes a hole blocking layer 308 (e.g., bathocuproine BCP) that prohibits an exciton diffusion process toward the electrode 312), and the electrode 312, which may be made of Ag.

[0031] The successful passivation of the NiO_x layer 212 is reflected in the enhancement of the open-circuit voltages (V_{oc}) of the passivated device 300 when

compared to a control device, as shown in Figure 5. For this parameter, it is noted that the C106 metal-organic complex achieves the highest voltage. The passivation eliminates the existence of the NiO_x surface defects acting as recombination centers, and thus, increases the voltage output of the devices without resulting in a drop in the short-circuit density (J_{sc}), as shown in Figure 6, and also without a drop in the fill factor (FF), as shown in Figure 7. Consequently, the passivation shown in Figure 3 increases the power conversion efficiency (PCE) of the solar cell 300, as illustrated in Figure 8. It is noted that the N719 dye achieves the best J_{sc} , FF, and PCE values, followed by the C106 dye.

[0032] Because the chemical composition of the metal-organic complex used as the passivation layer 310 can be selected to have various coordination numbers, or various core metal atoms, or various functional groups on the ligands, it is possible to tune the passivation layer to passivate any metal oxide surface. In other words, by selecting the type of metal-organic complex used to passivate a metal oxide layer, it is possible to use such passivation layer for any desired semiconductor device that uses a metal oxide layer.

[0033] The passivation layer discussed above may achieve further advantages as now discussed. The metal-organic complex passivation changes the electronic structure of the metal oxide that is passivated. Particularly, the chemical flexibility of the metal-organic complex passivation strategy paves the way to tune energy levels (conduction band minimum, valance band maximum, and work function) of any semiconducting metal oxide for any desired target application. This flexibility in selecting the metal-organic complex passivation layer widens the

applicability of metal oxides for use in photovoltaics, diodes, transistors, sensors, and any devices with a metal-oxide interface.

[0034] In another application, depending on the chemical nature of the metal-organic complex passivation molecule, the surface energy of the metal oxide that is being passivated can be tuned accordingly to obtain a metal oxide with very low-surface energy (hydrophobic surface) or a very high-surface energy (hydrophilic surface). In this application, a hydrophilic surface has a water contact angle less than 90° , whereas a hydrophobic surface forms a water contact angle higher than 90° . Tuning the surface energy of a metal oxide via the metal-organic complex passivation allows uniform deposition of a wide range of hydrophilic, hydrophobic or ambipolar materials on the metal oxide layer. This process also alters the work function of the metal oxide surface. Therefore, this advantage of the passivation process disclosed herein can widen the applicability of metal oxides for use in photovoltaic devices and transistors.

[0035] If needed, excess metal-organic complexes coated on the metal oxide surface can be washed away. This allow the formation of an atomically thin passivation layer 310, which is highly desirable in electronic devices as it allows transfer of charges with minimized resistive losses. Those skilled in the art would understand that anyone or a combination of the advantages discussed above may be achieved with the passivation process proposed in these embodiments.

[0036] Based on the observation that the novel passivation of surface defects of doped or pristine metal oxides 210 with a library of metal-organic complexes 400 improves the efficacy of the electronic devices 300 involving metal-oxide interfaces,

the inventors have discovered that the passivation process and the passivation metal-organic complexes shown in Figures 4A to 4F would improve the performance of many semiconductor devices that use a metal-oxide interface. Besides, the chemical flexibility of the metal-organic complexes 400 paves the way to attain metal oxides with highly tunable energy levels and surface energies, which is not feasible with the existing passivation strategies. Thus, in the following, various semiconductor device that can benefit from such passivation process are discussed.

[0037] Figure 9A shows an n-i-p solar cell 900 that generates an electrical current when exposed to light 902, and the electrical current can be used for powering a load 990. The light 902 enters through a transparent substrate 910 (e.g., Si). A bottom electrode 912 (e.g., ITO) may be formed on the substrate 910. An electron transport layer (n-type) 212, which may be made of a metal oxide, is formed on the bottom electrode 912. A surface 210 of the electron transport layer 212 may be passivated with the metal-oxide complex 400 as discussed above with regard to Figure 3, to form a passivation layer 310. The metal-oxide complex 400 may be any one shown in Figures 4A to 4F. A perovskite light absorber layer 914 is formed over the metal-oxide complex passivation layer 310, followed by the formation of a hole-transport layer (p-type) 916 over the perovskite layer 914. A buffer layer 918 is formed over the hole-transport layer 916 and a top electrode 920 is formed over the buffer layer 918 to complete the structure of the n-i-p solar cell 900.

[0038] A p-i-n solar cell 950 is shown in Figure 9B and may also be made to have the passivation layer 310 including the metal-oxide complex 400. The p-i-n solar cell 950 has the same layers as the n-i-p solar cell 950, except that the hole

transport layer 916 is formed on the electrode 912, the passivation layer 310 is formed over the hole transport layer 916, the perovskite layer 914 is formed over the passivation layer 310, and the electron transport layer 212 is formed over the perovskite layer 914. If other layers of the solar cells 900 and 950 are made of a metal oxide, they also may be passivated with a passivation layer 310, including the same metal-organic complex or another one, as discussed later.

[0039] The passivation layer 310 can also be used in the fabrication of light emitting diodes, as illustrated in Figures 10A and 10B. A metal oxide material can be used for the electrodes, electron- and hole-transport layers, and/or electron- and hole-injection layers for the fabrication of the light emitting diodes having either an n-i-p or p-i-n structure with respect to the illuminated light direction, and the passivation layer can be formed over any one of these metal oxide layers, over a combination of them, or over each of them.

[0040] More specifically, as illustrated in Figure 10A, an n-i-p light emitting diode (LED) 1000 has a transparent substrate 910, a transparent bottom electrode 912, an electron injection layer 1010 formed over the bottom electrode 912, and an electron transport layer 212, similar to the layer 212 in the solar cell 900 or 950, formed over the electron injection layer 1010. The electron transport layer 212 may be passivated with the passivation layer 310, which includes one or more of the metal-organic complexes 400, similar to the devices shown in Figures 9A and 9B. It is noted that the layers that are the same as in the solar cells of Figures 9A and 9B are labeled with the same reference numbers. Over the passivation layer 310, a light emitter layer 1012 is formed. The light emitter layer 1012 may include indium gallium

nitride (InGaN), gallium arsenide (GaAs), aluminum gallium indium phosphide (AlGaInP), or similar materials. A hole transport layer 916 is formed over the light emitter layer 1012. On top of the hole transport layer 916, a hole-injection layer 1014 is formed, which is covered with a top electrode 920. The LED 1050 includes similar layers, but disposed in a different order, as indicated in Figure 10B.

[0041] Although the passivation layer 310 that includes the metal-organic compound 400 is shown in Figures 10A and 10B being directly deposited over the electron transport layer 212 or the hole transport layer 916, those skilled in the art would understand that the passivation layer 310 can be formed over any metal oxide layer. Thus, because the electrodes 912 and 920 and the electron injection layer 1010 and the hole injection layer 1014 may also be made of a metal oxide material, the passivation layer 310 can also be formed over each and all of these layers, as schematically indicated by the layer 310'. Any number of these layers may be selected to be passivated with the metal-organic compound 400. In one application, all the passivation layers include the same metal-organic compound 400. In another application, different passivation layers include different metal-organic compounds. Different from the solar cells 900 and 950, the LEDs 1000 and 1050 use a power source 1090 that is coupled to the electrodes 912 and 920, and the light emitter layer 1012 generates light 902, which is emitted outside the LED.

[0042] Moreover, metal oxides can be employed as n-type or p-type semiconductors, and/or dielectric, gate, source and/or drain materials for fabrication of transistors which can have different structures. Figures 11A to 11E illustrate different configurations of such metal-oxide transistors. More specifically, Figure 11A

shows an n-channel metal-oxide transistor 1100 having a p-type semiconductor substrate 1102, an n-type semiconductor source 1104, an n-type semiconductor drain 1106, corresponding electrical connections 1105 and 1107, a gate 1108, and a corresponding electrical connection 1109. The passivation layer 310 can be formed on the substrate 1102, just below the gate 1108, between the source and the drain, and/or just on top of the gate 1108, as indicated by layer 310'.

[0043] The metal-oxide transistor 1150 shown in Figure 11B has a similar configuration, except that the n-type semiconductors are replaced by p-type semiconductors, and vice versa. More specifically, the transistor 1150 has an n-type semiconductor substrate 1152, a p-type semiconductor source 1154, a p-type semiconductor drain 1156, corresponding electrical connections 1155 and 1157, a gate 1158 and a corresponding electrical connection 1159. The passivation layer 310 can be formed on the substrate 1152, just below the gate 1158, between the source and the drain, and/or just on top of the gate 1158, as indicated by layer 310'.

[0044] Figure 11C shows another configuration for the metal-oxide transistor. The transistor 1180, which is a bottom-gate-bottom-contact configuration includes a substrate 1182, a gate pad 1184 made of a metal, a dielectric material 1186 formed on the gate pad 1184, source 1188 and drain 1190 formed on the dielectric material 1186, and a p- or n-type semiconductor material 1192 formed between and above the source and drain. As any of the gate pad 1184, or the dielectric material 1186 or the drain and source may be made of a metal-oxide material, the passivation layer 310 may be formed on one or more of these elements, as illustrated in Figure 11C. Additional passivation layers 310' and 310'', which include the same or different

metal-organic complexes as the passivation layer 310, may be formed on the various other metal oxide materials. Figure 11D shows the same elements forming a top-gate-bottom-contact transistor 1180' and Figure 11E shows a bottom-gate-top-contact transistor 1180'' also having the same elements as the transistor 1180. It is noted that only the vertical arrangement of the various elements varies for these transistors.

[0045] For photodetector applications, which are illustrated in Figures 12A and 12B, the metal-oxides can be used for electrodes, electron- and hole-transport materials, and/or buffer layers for the fabrication of the photo-detector 1200 having a vertical structure or a photo-detector 1250 having a horizontal structure. It should be noted that the vertical structure can have a p-i-n or n-i-p structure with respect to the light illumination. Also, the metal oxide material can be used as a gate, dielectric, source and/or drain for the fabrication of the photo-detector 1250. More specifically, the vertical structure in Figure 12A and the lateral structure in Figure 12B are independent from each other. Photo-detectors based on the vertical structure include photodiodes (also called photodiode-type photodetectors) and photo-multiplication (or called gain)-type photodetectors; whereas photodetectors based on the lateral structure include photoconductors and phototransistors. All photoconductors, photodiodes, and photomultiplication-type photodetectors are two-terminal devices with an anode and cathode. In contrast, the phototransistors are three-terminal devices with source, drain, and gate electrodes.

[0046] With regard to Figure 12A, the photodetector 1200 can have the same structure as the solar cells shown in Figures 9A and 9B, and for this reason, the

specific structure of the photodetector 1200 is not repeated herein. If a light 902 illuminates the light absorber layer 914, the light is used to generate pairs of electrons and holes, which are separated and transported to different electrodes 912 and 920, so that a load 990 can use the generated electrical current.

[0047] However, if the photodetector is implemented to have a lateral structure, as illustrated in Figure 12B, then this type of photodetector 1250 includes a substrate 1252, a gate pad 1254 formed on the substrate 1252, a dielectric layer 1256, and a light absorber layer 1258 formed over the dielectric layer 1256. Source 1258 and drain 1260 are formed on the light absorber layer 1258 for extracting the electrical current generated due to the impinging light 902. Depending on which layer is made of a metal-oxide, the passivation layer 310 can be formed on the substrate 1254, and/or on the dielectric layer 1256, and/or on the light absorber layer 1258.

[0048] Metal oxide materials can also be used as sensing, dielectric and/or electrode materials for the fabrication of general sensors. Such a sensor 1300 is illustrated in Figure 13 and includes a substrate 1302, which may be made of a metal oxide material, a passivation layer 310 applied over the substrate 1302, a dielectric material 1303 formed on the substrate 1302 or the passivation layer 310, where the dielectric material may be made of a metal-oxide, another passivation layer 310' applied as previously discussed, electrodes 1304 and 1306 for applying or collecting an electrical current, and a sensing material 1310. If the sensing material 1310 is made from a metal oxide material, yet another passivation layer 310'' may be applied to a surface of this layer. The sensing material 1310 may be sensitive to any one factor as light, temperature, humidity, one or more chemicals, etc. An interaction of

the sensing material 1310 with the factor noted above may determine the generation of an electrical current, which is collected by the electrodes 1304 and 1306.

[0049] For the applications discussed above, a wide range of materials may be used. For example, for any layer that uses a metal oxide material, the metal oxide may include beryllium oxide (BeO_x), magnesium oxide (MgO_x), calcium oxide (CaO_x), strontium oxide (SrO_x), barium oxide (BaO_x), titanium oxide (TiO_x), zirconium oxide (ZrO_x), hafnium oxide (HfO_x), vanadium oxide (VO_x), niobium oxide (NbO_x), tantalum oxide (TaO_x), chromium oxide (CrO_x), molybdenum oxide (MoO_x), tungsten oxide (WO_x), manganese oxide (MnO_x), iron oxide (FeO_x), cobalt oxide (CoO_x), nickel oxide (NiO_x), copper oxide (CuO_x), zinc oxide (ZnO_x), aluminum oxide (AlO_x), gallium oxide (GaO_x), indium oxide (InO_x), antimony oxide (SbO_x), cerium oxide (CeO_x), lanthanum oxide (LaO_x), thallium oxide (ThO_x), lithium oxide (LiO_x), silicon oxide (SiO_x), germanium oxide (GeO_x), tin oxide (SnO_x), lead oxide (PbO_x), arsenic oxide (AsO_x), antimony oxide (SbO_x), bismuth oxide (BiO_x), selenium oxide (SeO_x), tellurium oxide (TeO_x), ruthenium oxide (RuO_x), hydrogen-doped indium oxide (IHO_x) and fluorine-doped tin oxide (FTO_x).

[0050] The metal oxide layers can also contain a combination of two or more of the above metals such as indium-doped tin oxide ($\text{I}_a\text{T}_b\text{O}_x$), indium zinc oxide ($\text{I}_a\text{Z}_b\text{O}_x$), zirconium-doped Indium oxide ($\text{I}_a\text{ZR}_b\text{O}_x$), aluminum-doped zinc oxide ($\text{A}_a\text{Z}_b\text{O}_x$), zinc tin oxide ($\text{Z}_a\text{T}_b\text{O}_x$), indium gallium oxide ($\text{I}_a\text{G}_b\text{O}_x$), indium yttrium oxide ($\text{I}_a\text{Y}_b\text{O}_x$), copper gallium oxide ($\text{Cu}_a\text{Ga}_b\text{O}_x$), strontium copper oxide ($\text{Sr}_a\text{Cu}_b\text{O}_x$), copper chromium oxide ($\text{Cu}_a\text{Cr}_b\text{O}_x$), zirconium aluminum oxide ($\text{Z}_a\text{A}_b\text{O}_x$), indium–gallium–zinc oxide ($\text{I}_a\text{G}_b\text{Z}_c\text{O}_x$), indium yttrium zinc oxide ($\text{I}_a\text{Y}_b\text{Z}_c\text{O}_x$), indium lanthanum

zinc oxide (LaLbZcO_x) and barium strontium titanium oxide ($\text{Ba}_a\text{Sr}_b\text{Ti}_c\text{O}_x$). Here, the parameters a, b and c represent different metal ratios satisfying the $a + b + c = 1$ and $0 \leq a, b, c \leq 1$ conditions. Also, x represents the oxygen ratio wherein $0 \leq x \leq 4$.

Those skilled in the art would also understand that the substrates for all these devices may include Si, SiO, SiC, sapphire, etc, the electrodes may be made of any material, e.g., Ag, Cu, Au, etc., and the light emitting material may include aluminum gallium arsenide, aluminum gallium indium phosphide, aluminum gallium nitride, aluminum nitride, gallium arsenide, gallium arsenide phosphide, gallium phosphide, indium gallium nitride, indium gallium phosphide, etc. The light absorbing materials may include various semiconducting materials, for example, crystalline silicon, monocrystalline silicon, cadmium telluride, copper indium gallium selenide, silicon thin films, gallium arsenide thin film, perovskite materials, etc.

[0051] A method for making a semiconductor device 300, 900, 950, 1000, 1050, 1200, 1250 as discussed above is now discussed with regard to Figure 14. The method includes a step 1400 of forming a first electrode 302, a step 1402 of depositing a metal-oxide layer 212 over the first electrode 302, a step 1404 of forming a passivation layer 310 directly over a surface 210 of the metal-oxide layer 212, a step 1406 of forming an active layer 304 over the passivation layer 310, where the active layer 304 is configured to transform light 305 into electrical charges 320, 322 or to transform electrical charges 320, 322 into the light 305, and a step 1408 of forming a second electrode 312 over the active layer 304, where the second electrode is configured to channel the electrical charges 320, 322. The passivation layer 310 includes a metal-organic complex 400.

[0052] The disclosed embodiments provide a system having one or more metal oxide layers, which are passivated with a metal-organic complex for reducing defects and/or in-gap states in the surface of the metal oxide layer, which results in a better collection or transfer of electric charges. It should be understood that this description is not intended to limit the invention. On the contrary, the embodiments are intended to cover alternatives, modifications and equivalents, which are included in the spirit and scope of the invention as defined by the appended claims. Further, in the detailed description of the embodiments, numerous specific details are set forth in order to provide a comprehensive understanding of the claimed invention. However, one skilled in the art would understand that various embodiments may be practiced without such specific details.

[0053] Although the features and elements of the present embodiments are described in the embodiments in particular combinations, each feature or element can be used alone without the other features and elements of the embodiments or in various combinations with or without other features and elements disclosed herein.

[0054] This written description uses examples of the subject matter disclosed to enable any person skilled in the art to practice the same, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the subject matter is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims.

WHAT IS CLAIMED IS:

1. A semiconductor device (300, 900, 950, 1000, 1050, 1200, 1250) comprising:
 - a first electrode (302);
 - a metal oxide layer (212) formed over the first electrode (302);
 - a passivation layer (310) formed over a surface (210) of the metal oxide layer (212);
 - an active layer (304) configured to transform light (305) into electrical charges (320, 322) or to transform electrical charges (320, 322) into the light (305); and
 - a second electrode (312) formed over the active layer (304) and configured to channel the electrical charges (320, 322),wherein the passivation layer (310) includes a metal-organic complex (400).
2. The device of Claim 1, wherein the metal-organic complex includes ruthenium.
3. The device of Claim 2, wherein the metal-organic complex is one of $C_{26}H_{16}N_6O_8RuS_2$, $C_{58}H_{86}N_8O_8RuS_2$, $C_{44}H_{44}N_6O_4RuS_6$, $C_{52}H_{52}N_6O_6RuS_2$, $C_{42}H_{56}N_6O_4RuS_2$, and/or $C_{69}H_{117}N_9O_6RuS_3$.
4. The device of Claim 1, wherein the metal-oxide complex includes a metal atom and plural organic ligands.

5. The device of Claim 4, wherein each of the plural organic ligands are chemically connected to the metal atom.

6. The device of Claim 5, wherein the organic ligands are connected to the metal atom through one or more of carbon, nitrogen, oxygen, sulfur, phosphorus, or halide atoms.

7. The device of Claim 5, wherein one or more of the plural organic ligands include a functional group that directly connects to the surface of the metal oxide layer.

8. The device of Claim 7, wherein the functional group includes one or more of carboxylic acid, phosphonic acid, carboxylate, cyanide, alcohol, ester, ketone, amine, amide, ether, thiocyanate, aldehyde, sulfide, sulfonic acid, sulfone and heterocycle (N, S, O) groups.

9. The device of Claim 1, wherein the active layer is a light absorber material and the device is a solar cell.

10. The device of Claim 1, wherein the active layer is a light emitter material and the device is a light emitting diode.

11. The device of Claim 1, wherein the active layer is a light absorber material and the device is a photo-detector.

12. The device of Claim 1, wherein the metal oxide layer is an electron transport layer or a hole transport layer.

13. The device of Claim 1, further comprising:
an electron injection layer formed between the first electrode and the metal oxide layer; and
a hole transport layer formed between the second electrode and the active layer.

14. A semiconductor device (1100, 1150, 1180, 1300) comprising:
a substrate (1102, 1152, 1182, 1302) that includes a metal oxide material;
a passivation layer (310) formed directly over a surface of the substrate (1102, 1152, 1182, 1302);
an active layer (1108, 1158, 1192, 1310) configured to respond to a change in an external parameter;
a first electrode (1104, 1154, 1188, 1304) formed over a first part of the substrate (1102, 1152, 1182, 1302); and
a second electrode (1106, 1156, 1190, 1306) formed over a second part of the substrate (1102, 1152, 1182, 1302),
wherein the passivation layer (310) includes a metal-organic complex (400).

15. The device of Claim 14, wherein the metal-organic complex includes ruthenium.

16. The device of Claim 15, wherein the metal-organic complex is one of $C_{26}H_{16}N_6O_8RuS_2$, $C_{58}H_{86}N_8O_8RuS_2$, $C_{44}H_{44}N_6O_4RuS_6$, $C_{52}H_{52}N_6O_6RuS_2$, $C_{42}H_{56}N_6O_4RuS_2$, and/or $C_{69}H_{117}N_9O_6RuS_3$.

17. The device of Claim 14 wherein the metal-oxide complex includes a metal atom and plural organic ligands and each of the plural organic ligands are chemically connected to the metal atom.

18. The device of Claim 14, wherein the active layer is a gate, the first electrode is a source and the second electrode is a drain, and the parameter is an electrical current.

19. The device of Claim 14, wherein the active layer is a sensing material.

20. A method for making a semiconductor device (300, 900, 950, 1000, 1050, 1200, 1250), the method comprising:

forming (1400) a first electrode (302);

depositing (1402) a metal oxide layer (212) over the first electrode (302);

forming (1404) a passivation layer (310) directly over a surface (210) of the metal oxide layer (212);

forming (1406) an active layer (304) over the passivation layer (310), wherein the active layer (304) is configured to transform light (305) into electrical charges (320, 322) or to transform electrical charges (320, 322) into the light (305); and

forming (1408) a second electrode (312) over the active layer (304), wherein the second electrode is configured to channel the electrical charges (320, 322),

wherein the passivation layer (310) includes a metal-organic complex (400).

100

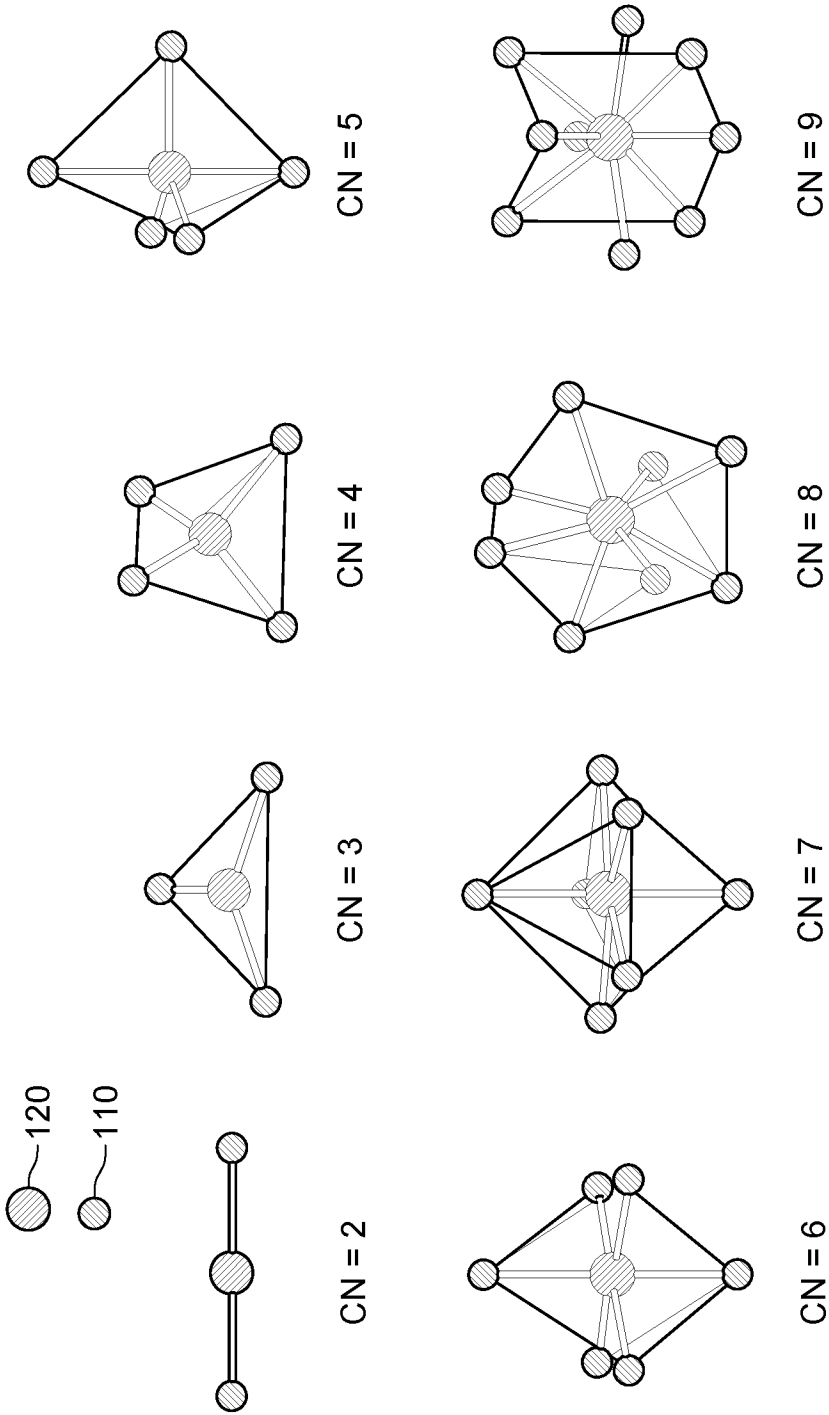


FIG. 1

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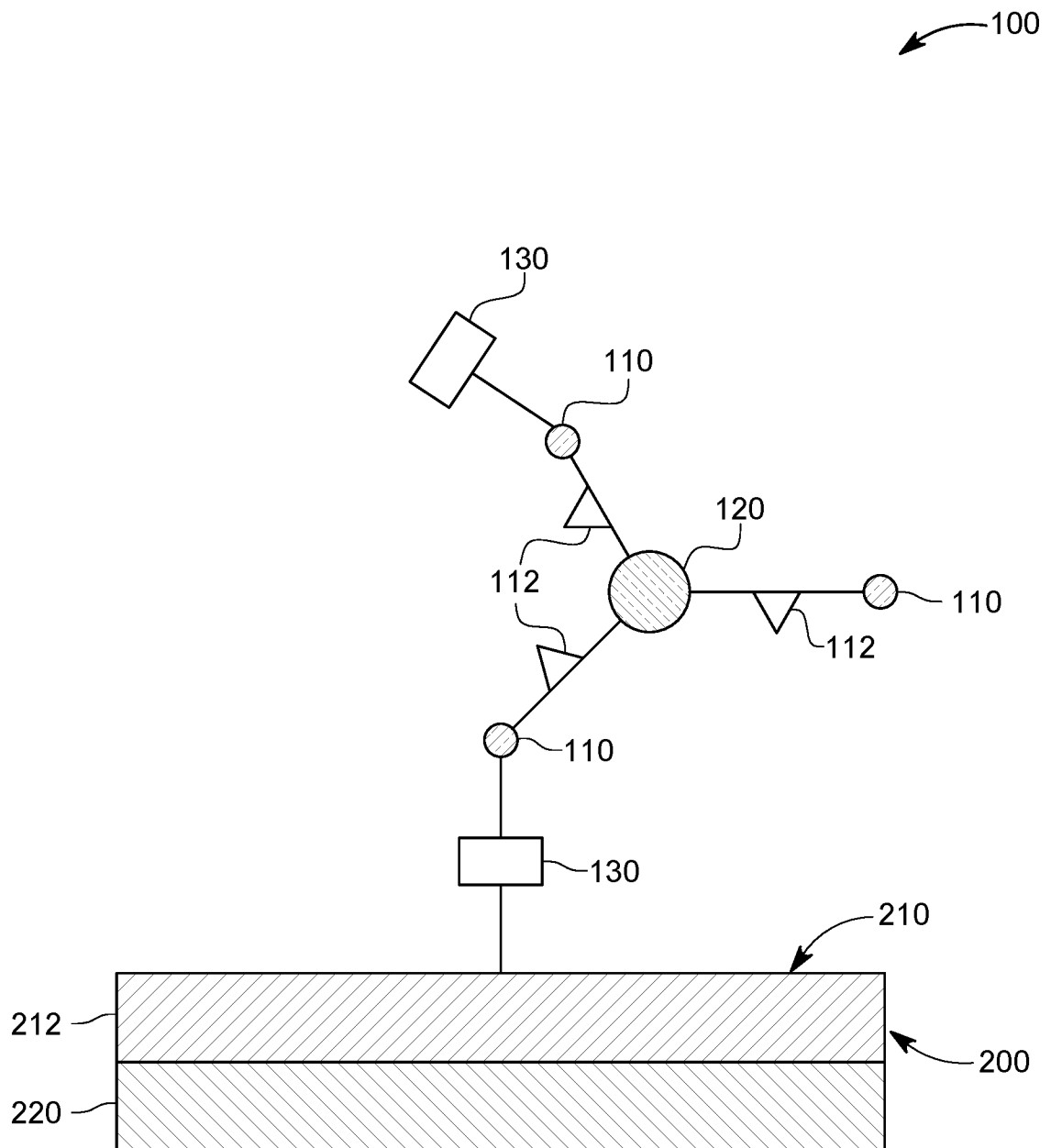


FIG. 2

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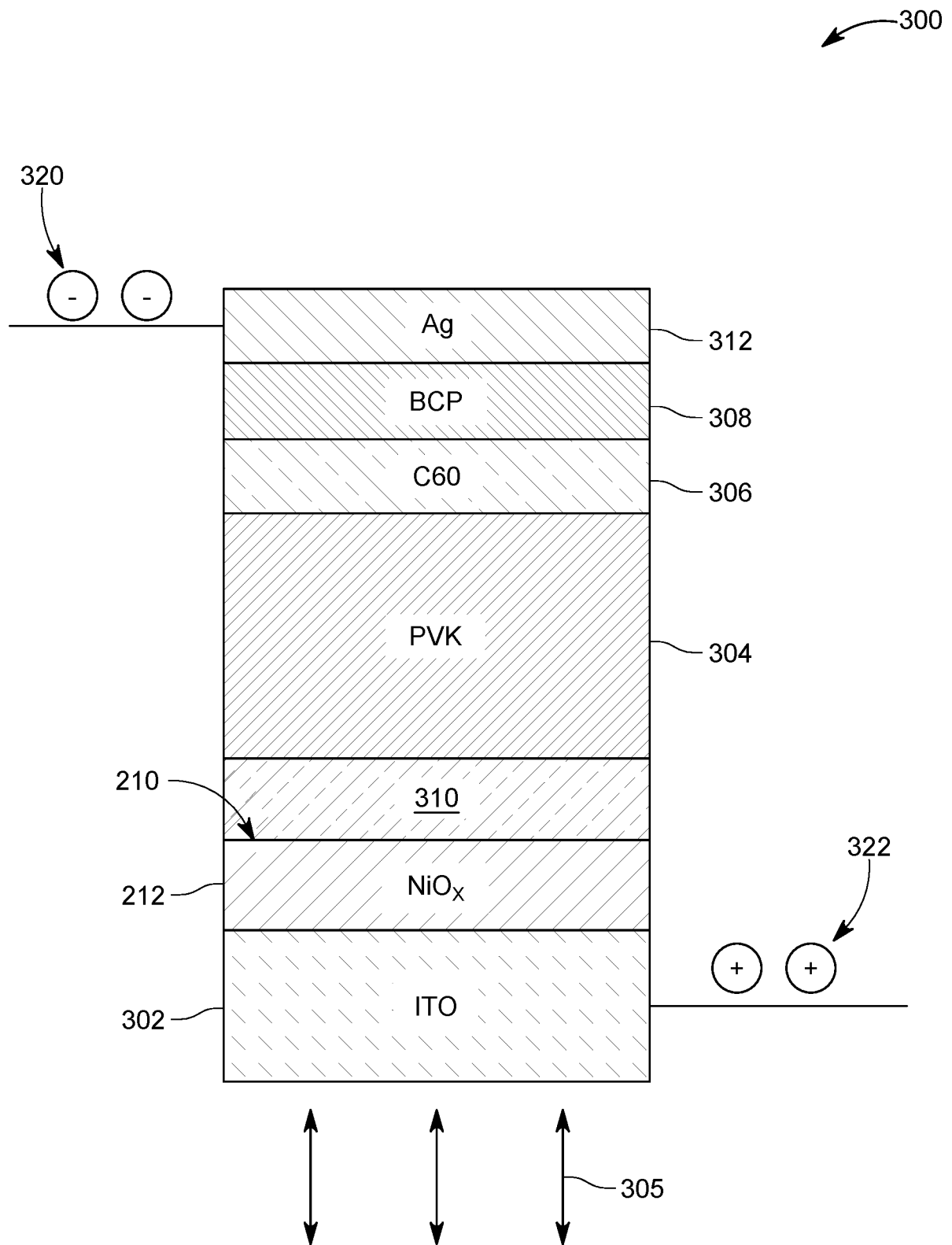


FIG. 3

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400

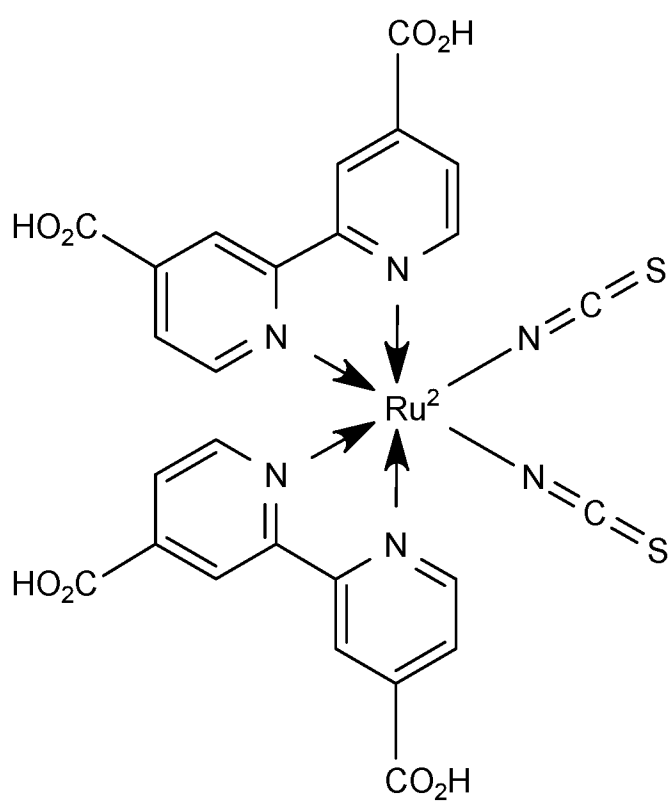
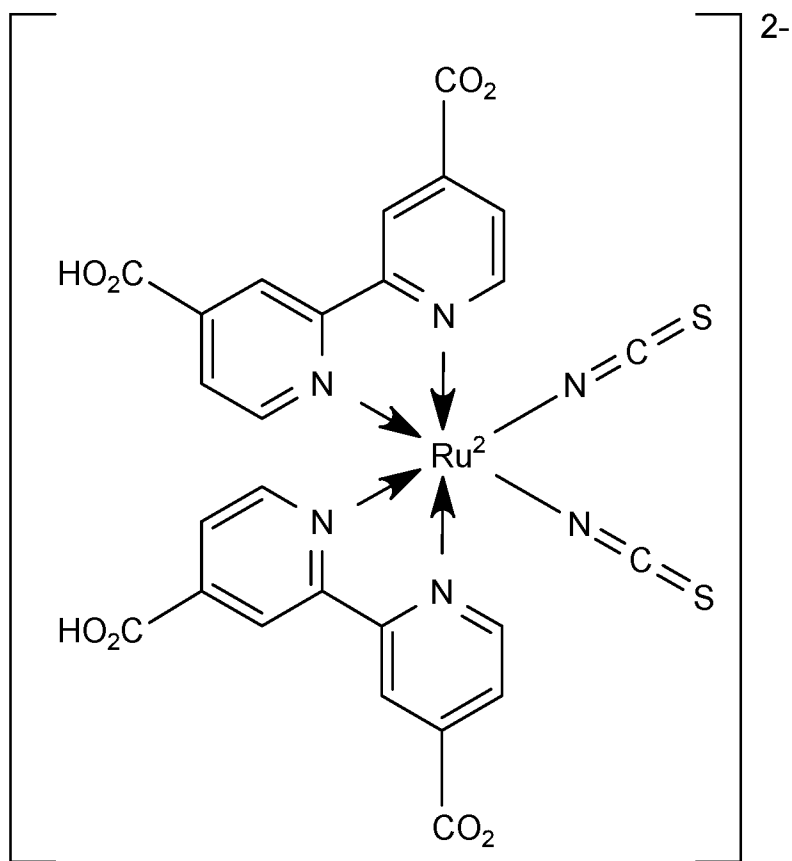
**N-3** $\text{C}_{26}\text{H}_{16}\text{N}_6\text{O}_8\text{RuS}_2$

FIG. 4A

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400



N-719
 $C_{58}H_{86}N_8O_8RuS_2$

FIG. 4B

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400

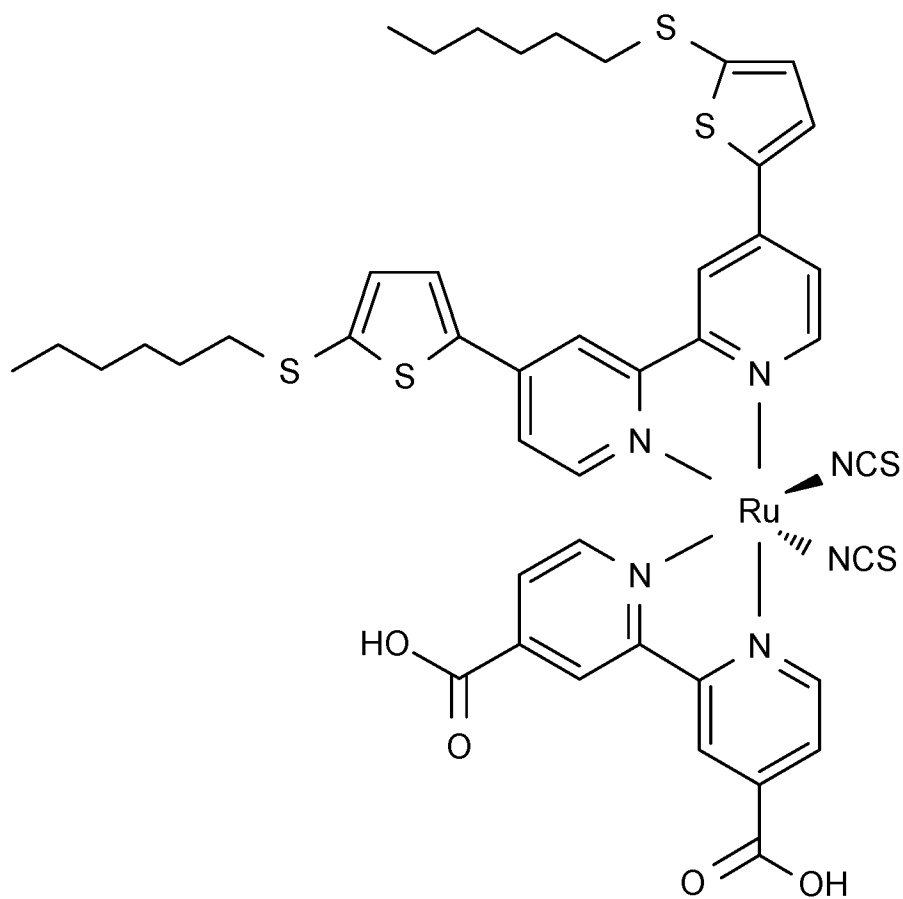
**C106** $\text{C}_{44}\text{H}_{44}\text{N}_6\text{O}_4\text{RuS}_6$

FIG. 4C

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400

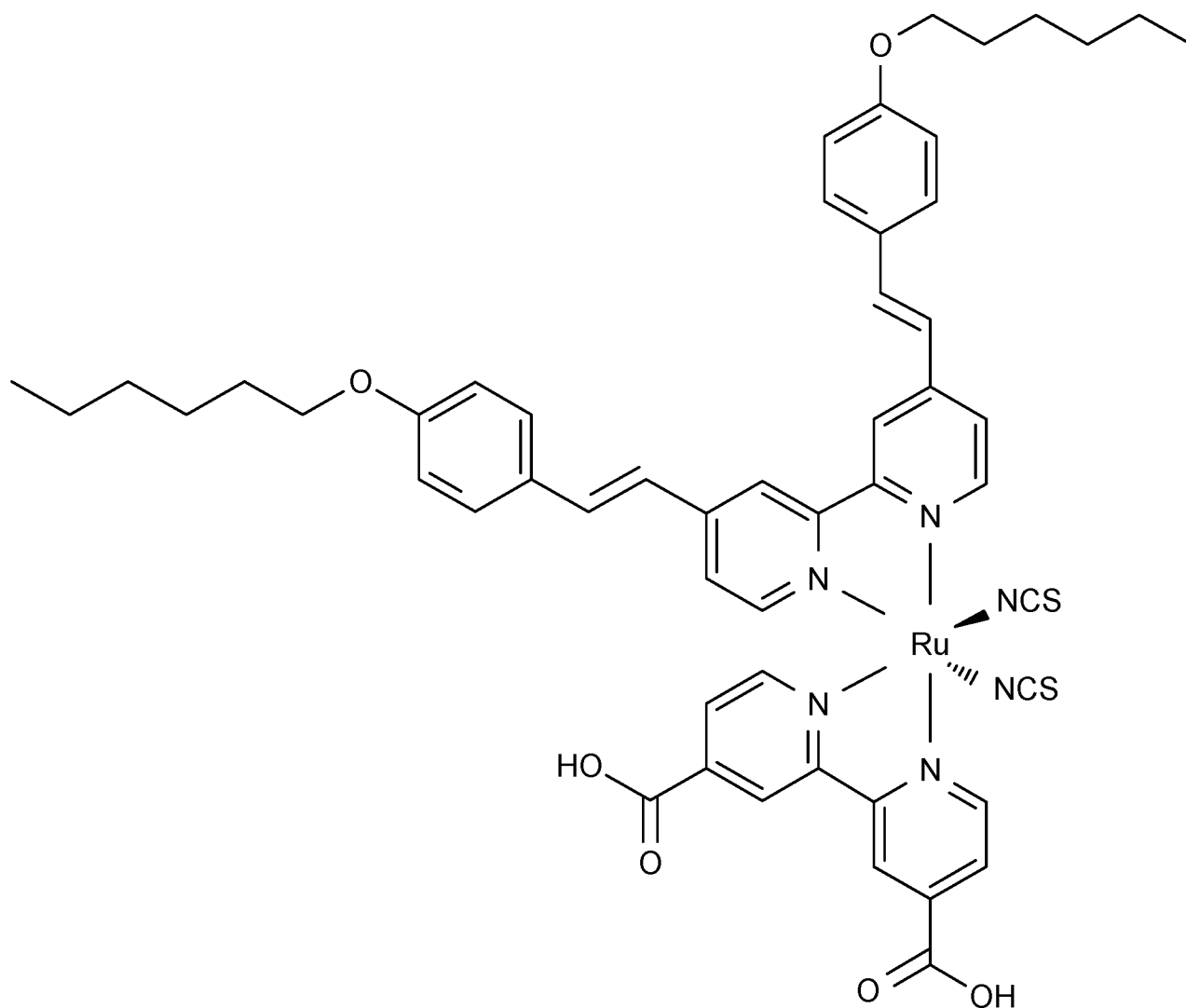
**K19** $C_{52}H_{52}N_6O_6RuS_2$

FIG. 4D

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400

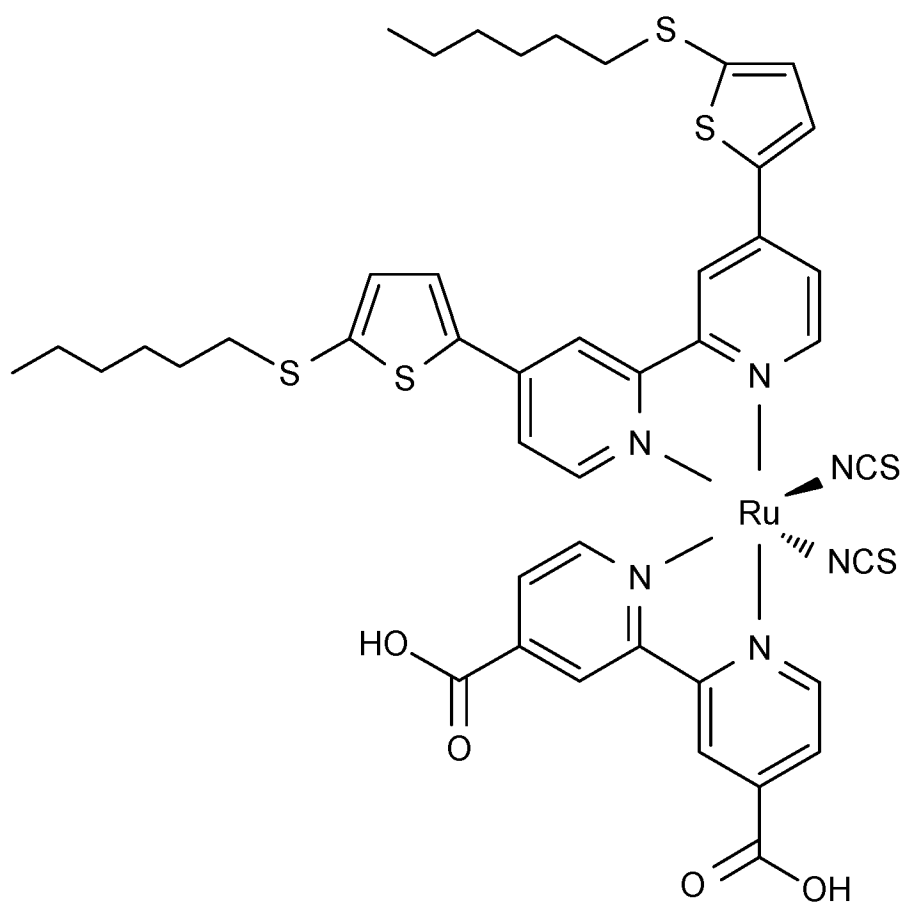
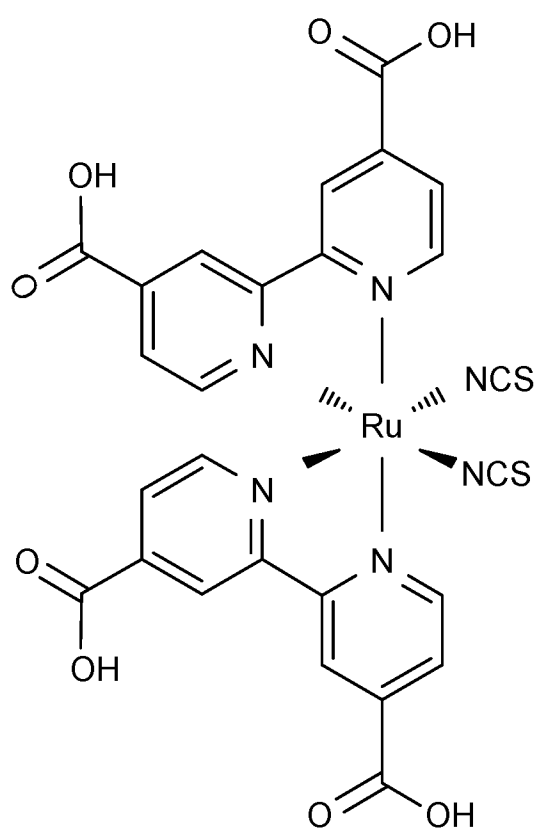
**Z907** $C_{42}H_{52}N_6O_4RuS_2$

FIG. 4E

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400

**N749** $\text{C}_{69}\text{H}_{117}\text{N}_9\text{O}_6\text{RuS}_3$ **FIG. 4F**

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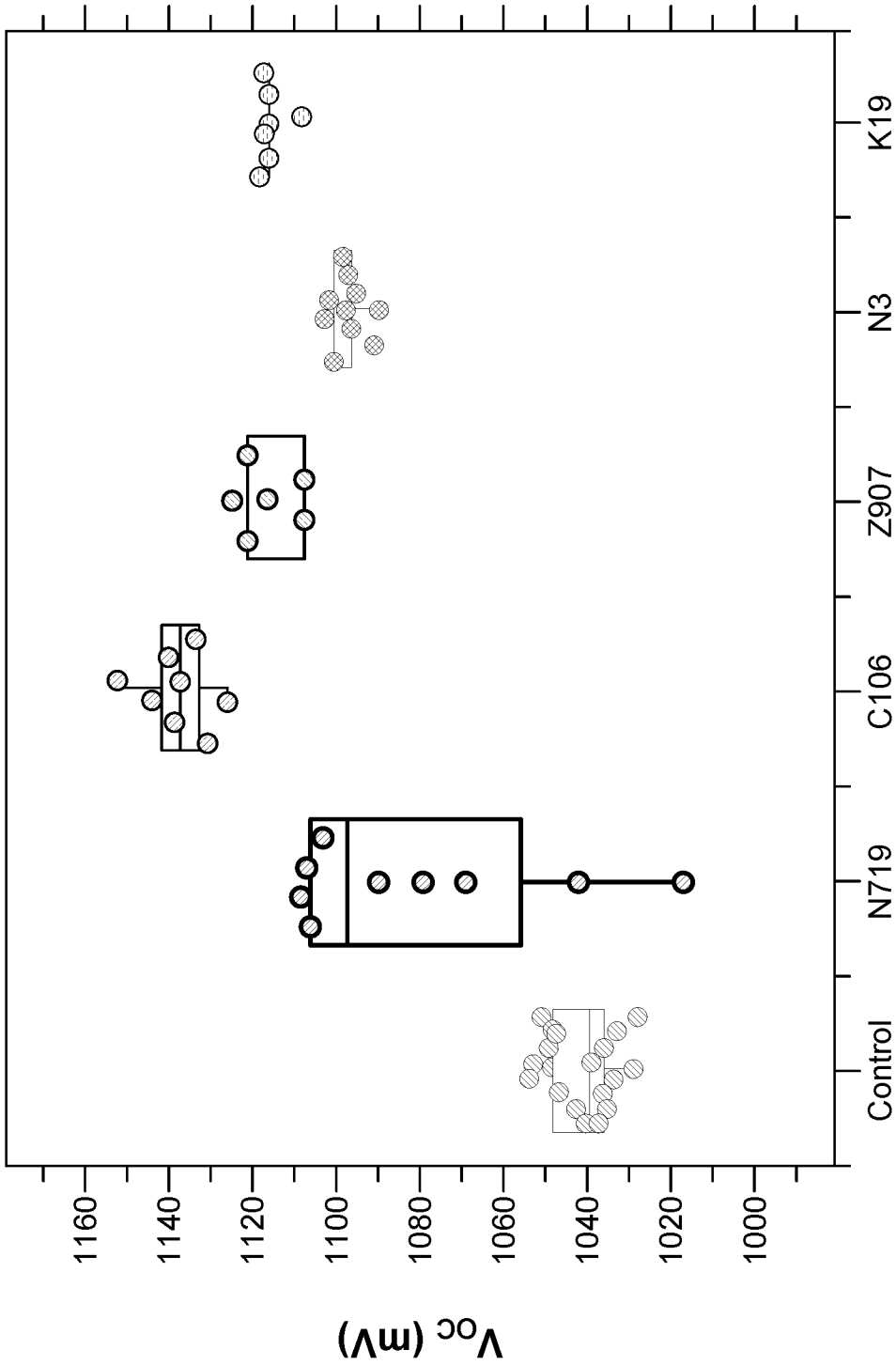


FIG. 5

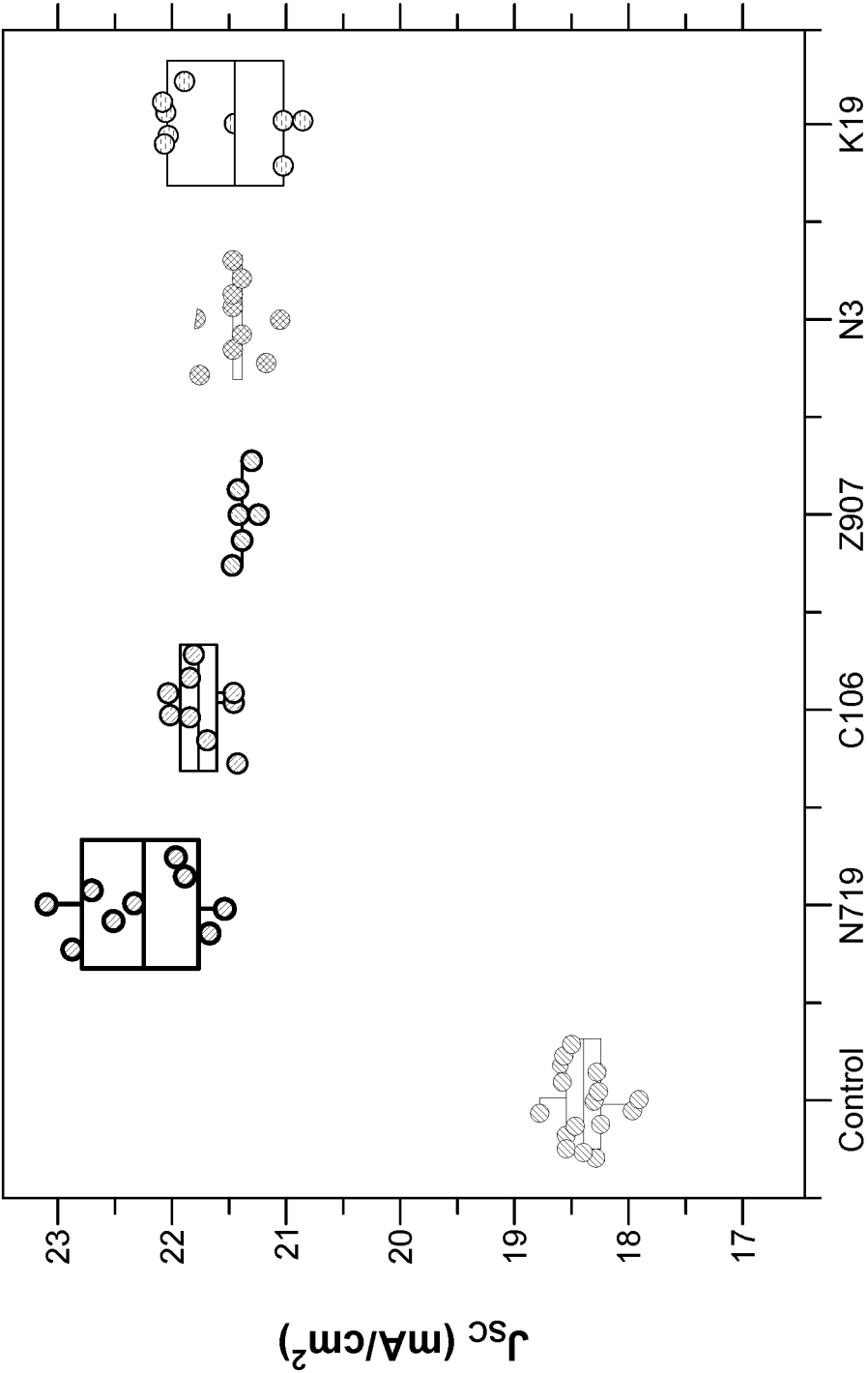


FIG. 6

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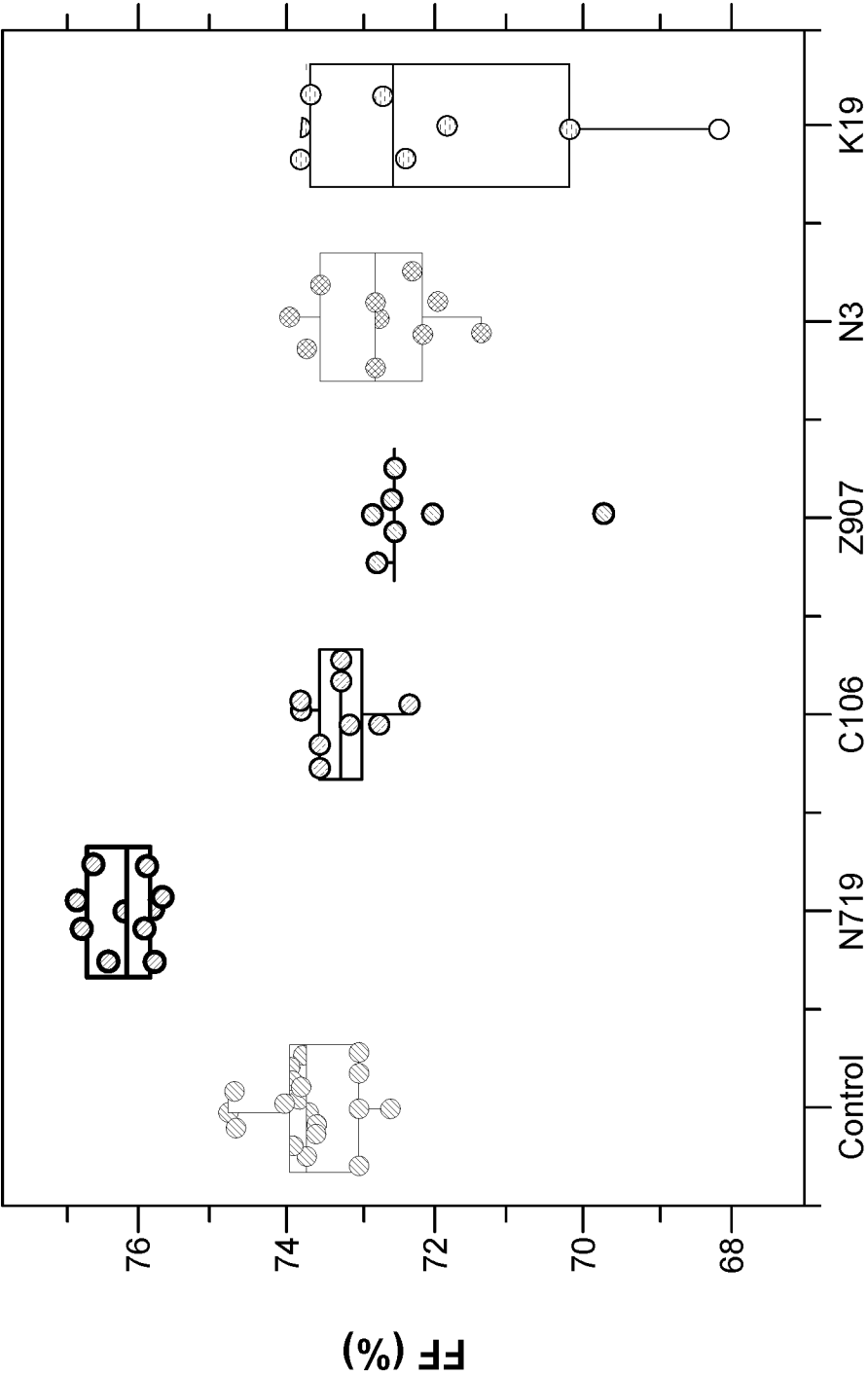


FIG. 7

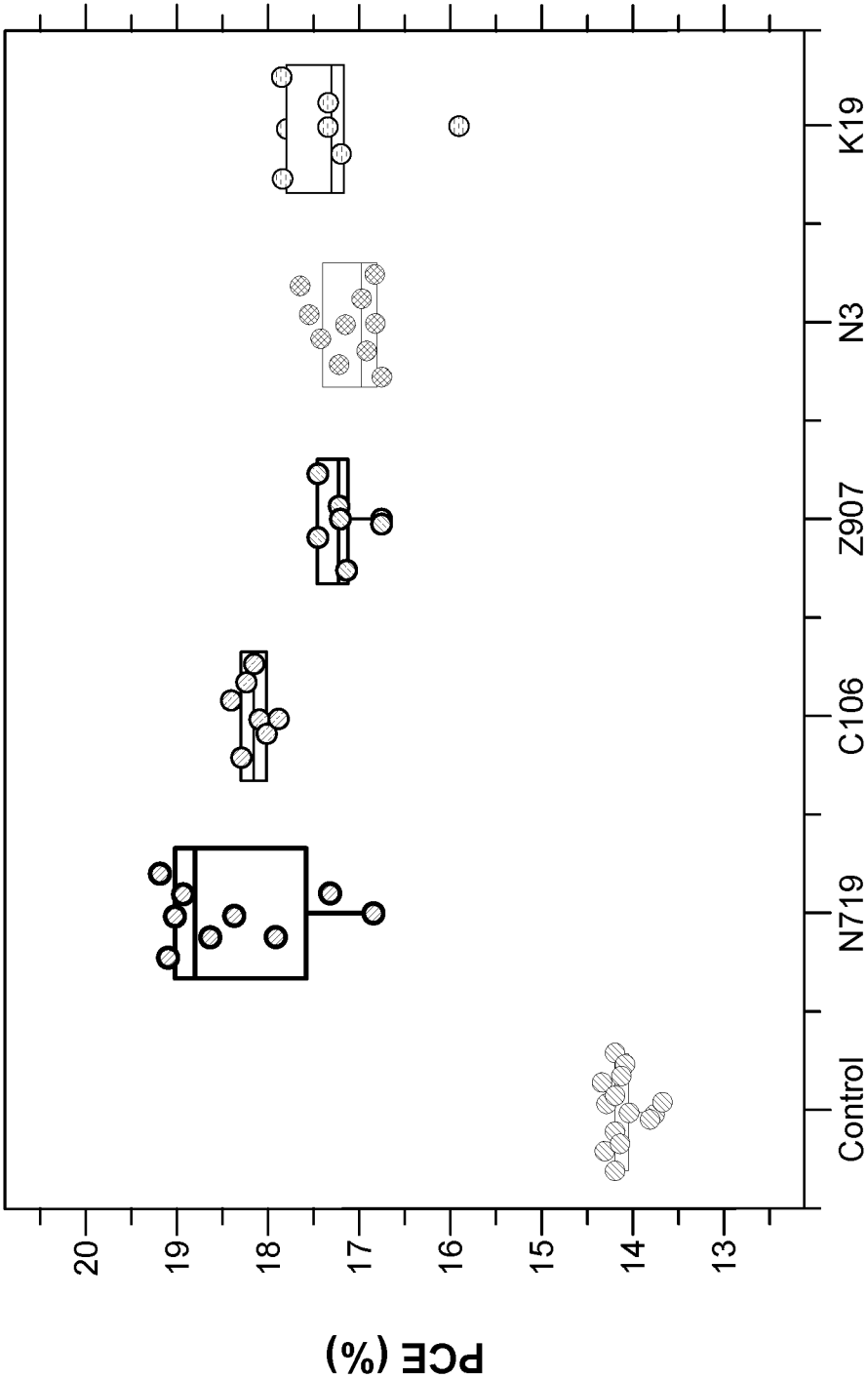


FIG. 8

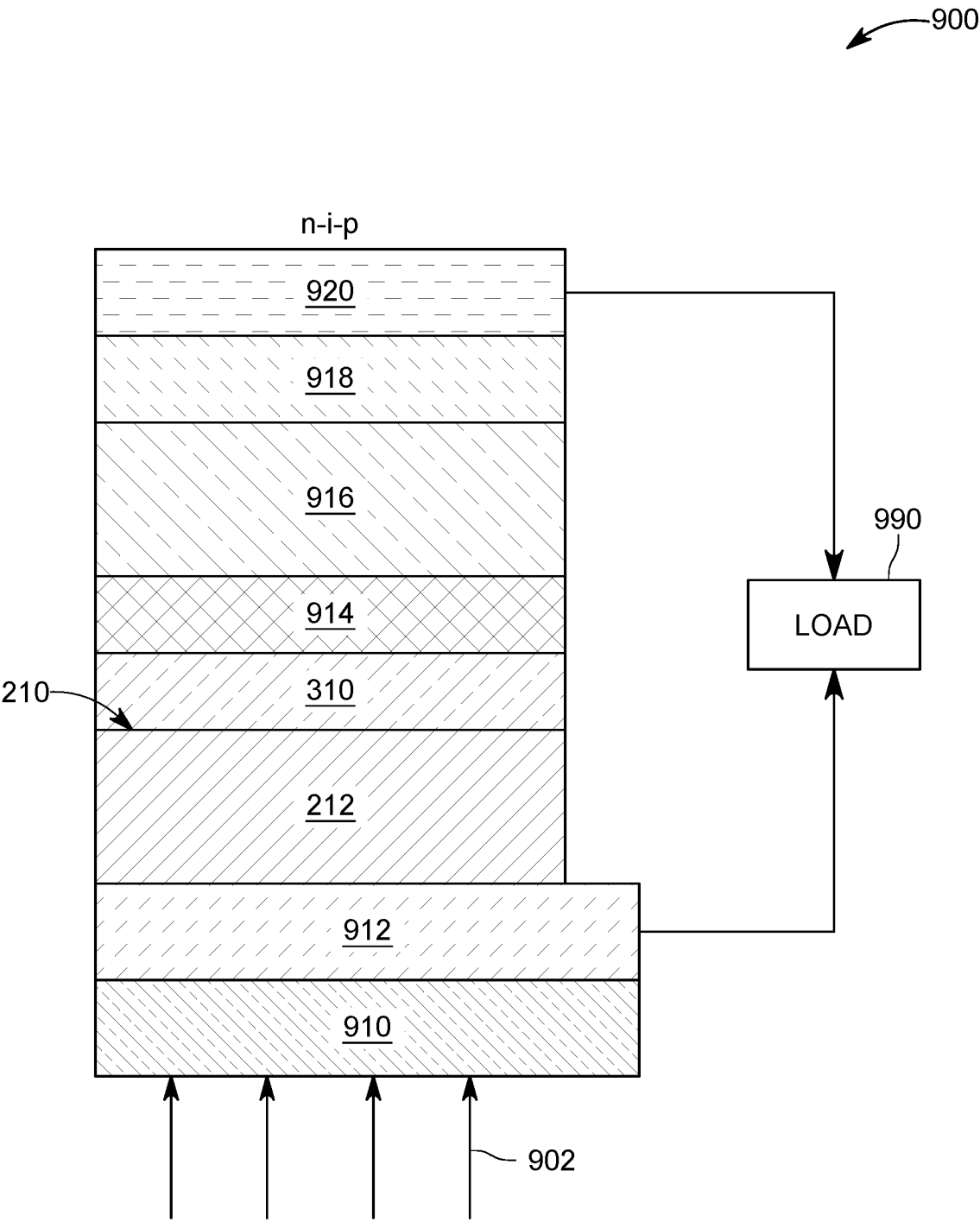


FIG. 9A

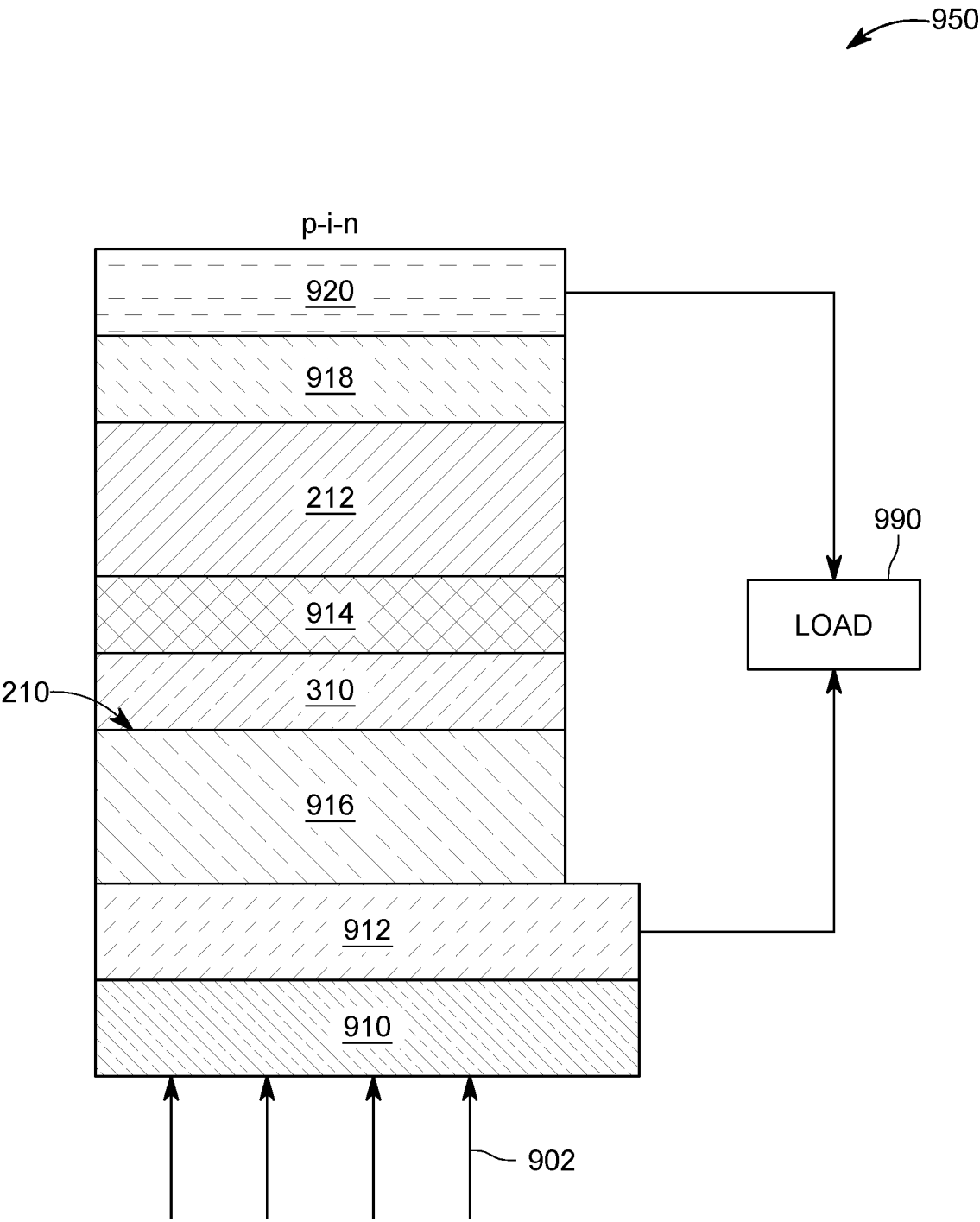


FIG. 9B

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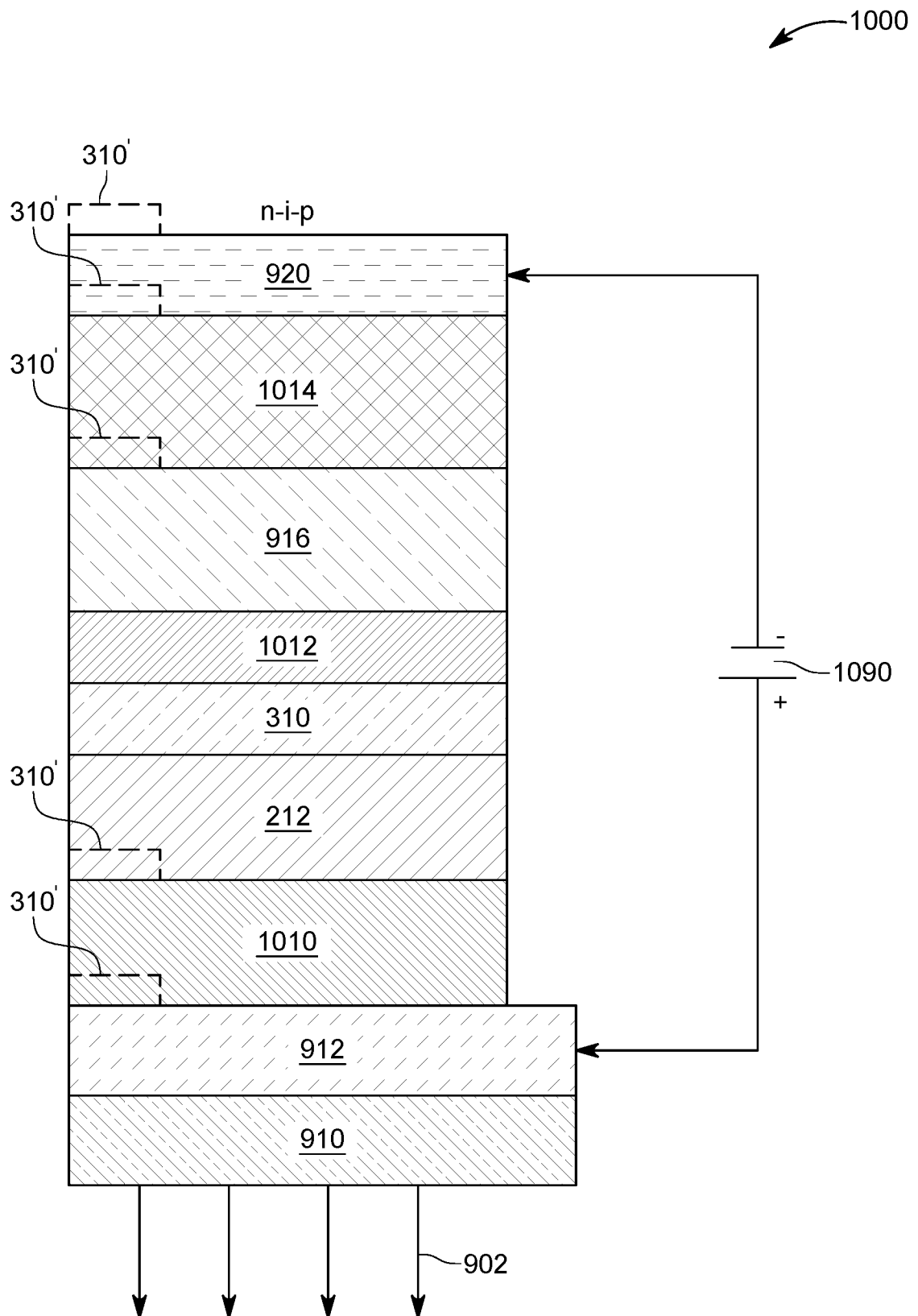


FIG. 10A

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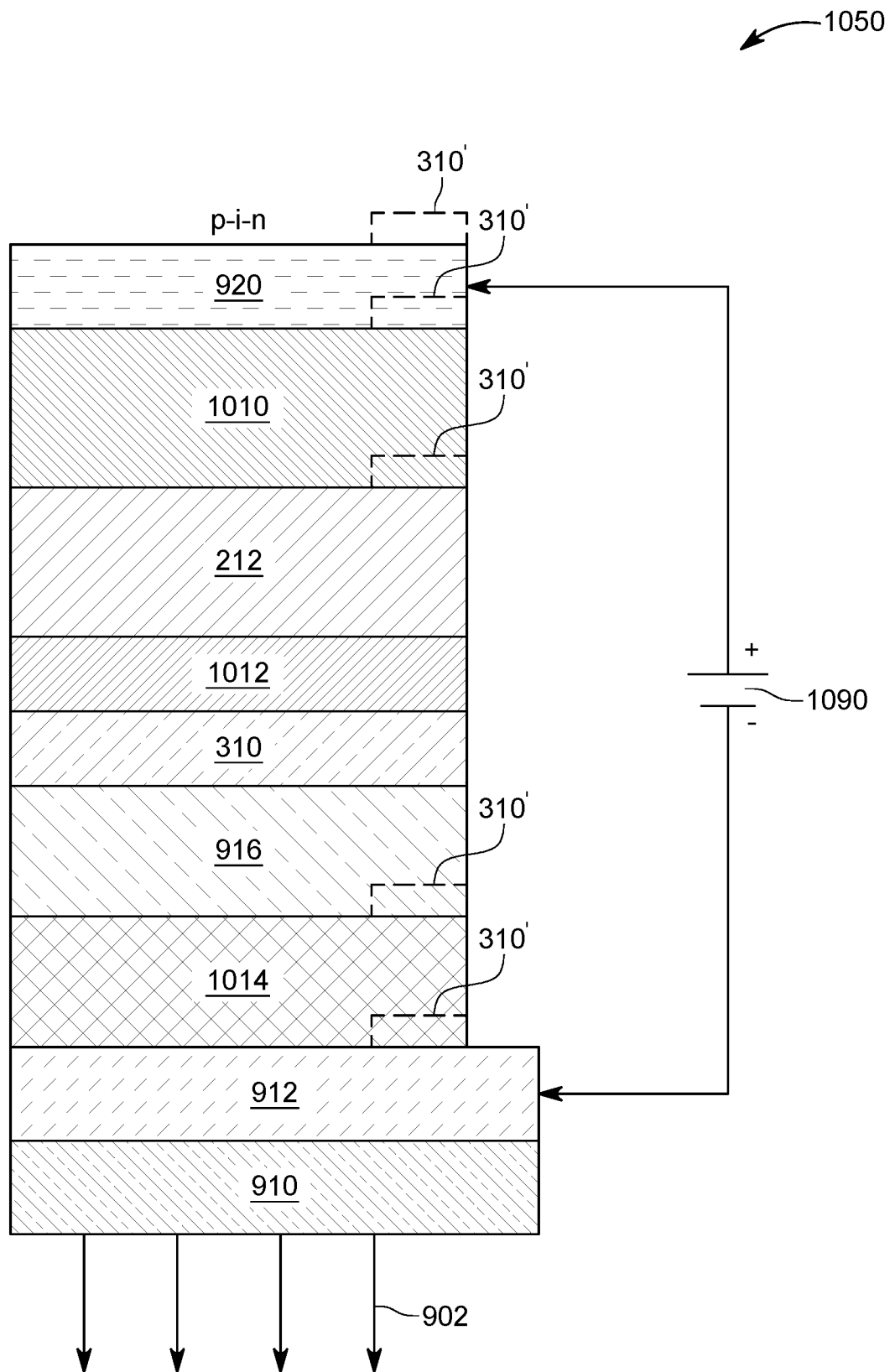


FIG. 10B

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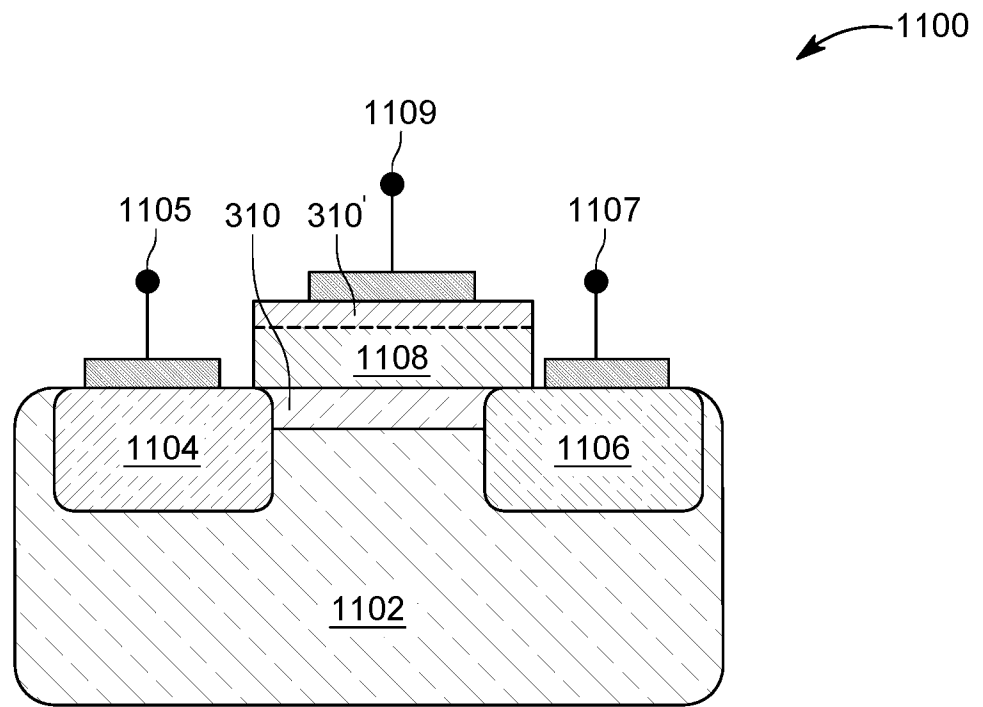


FIG. 11A

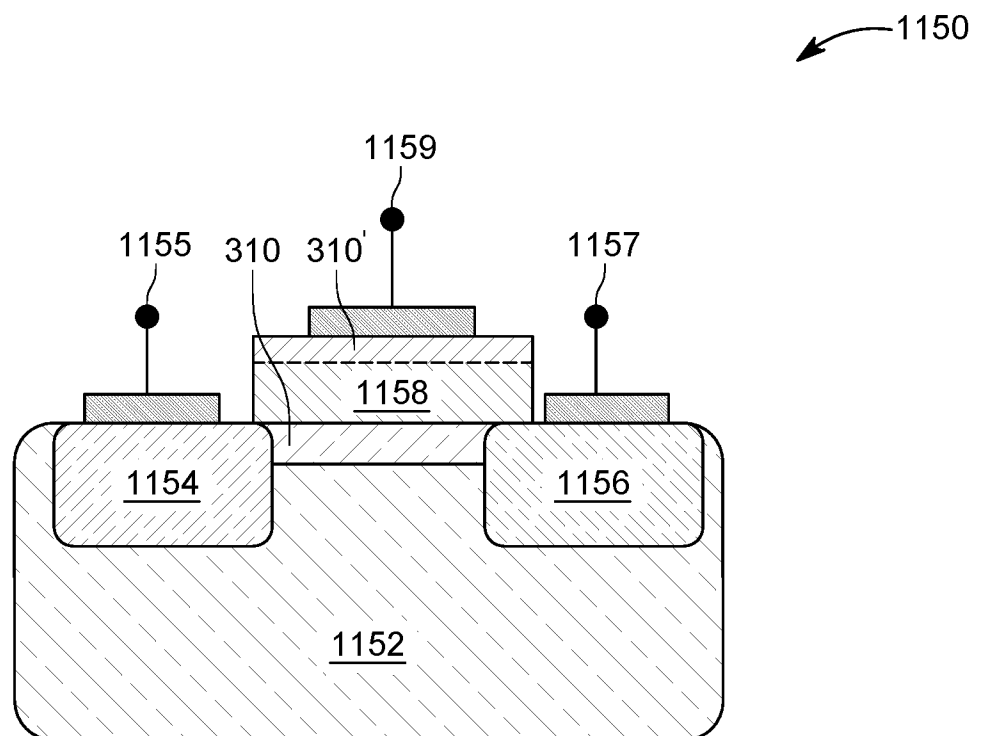


FIG. 11B

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1180

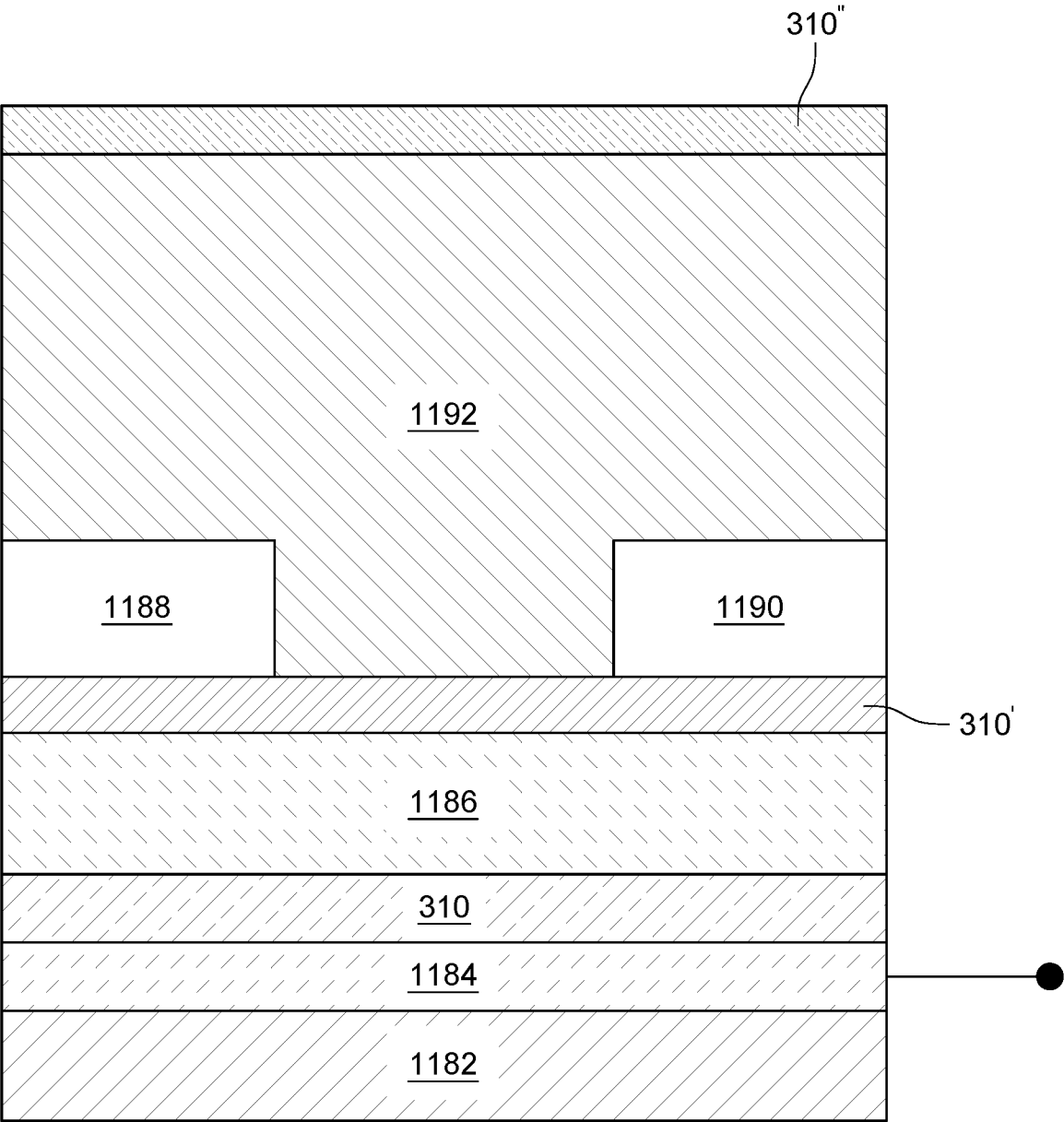


FIG. 11C

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1180'

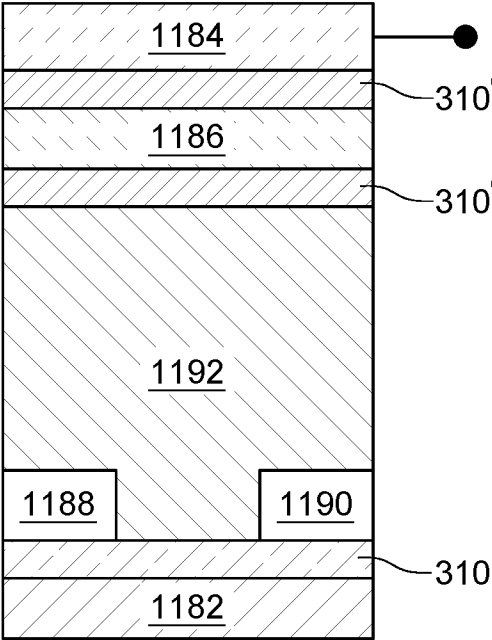


FIG. 11D

1180''

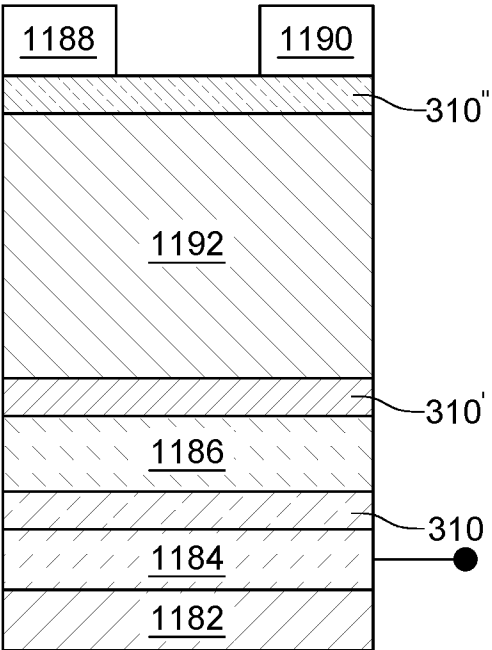


FIG. 11E

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1200

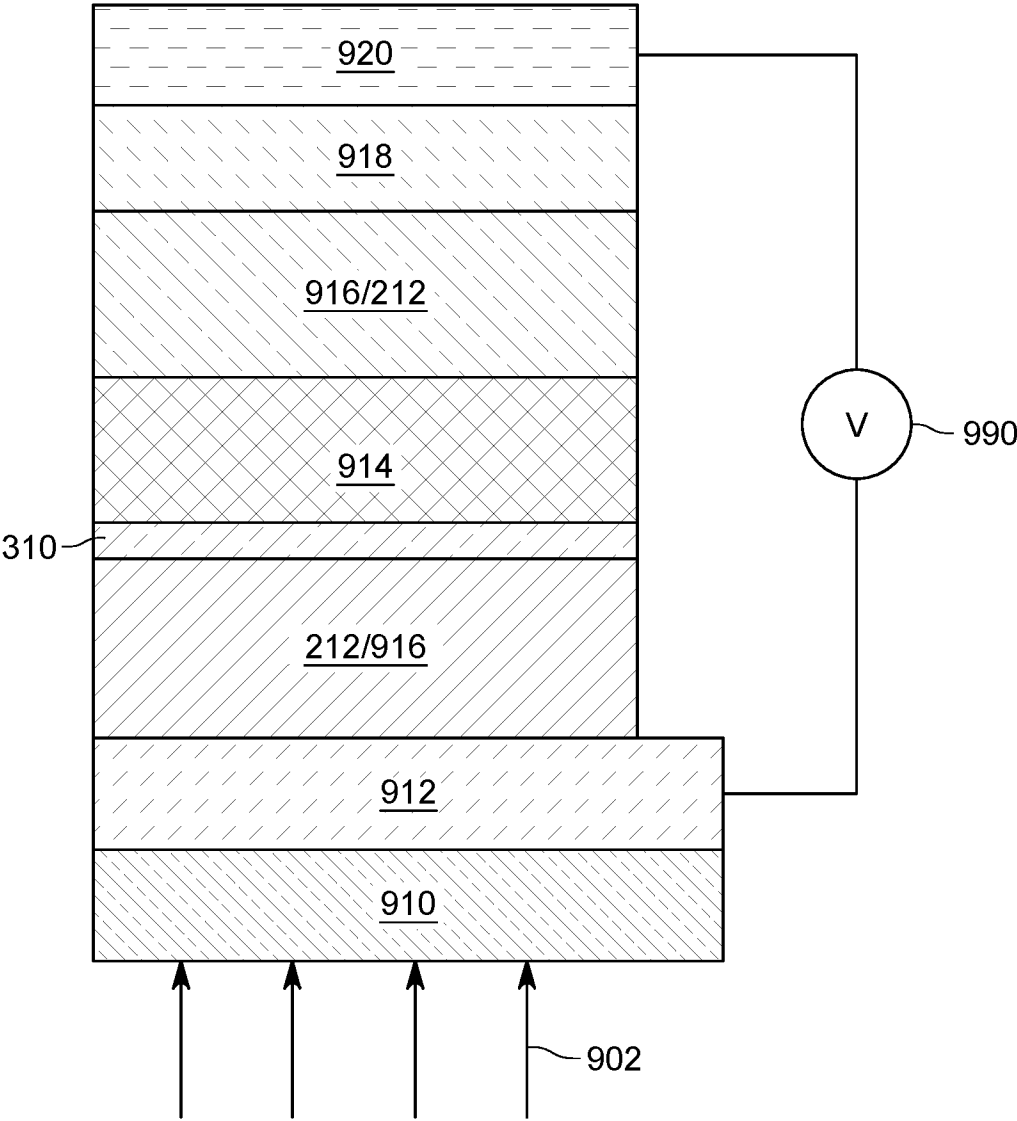


FIG. 12A

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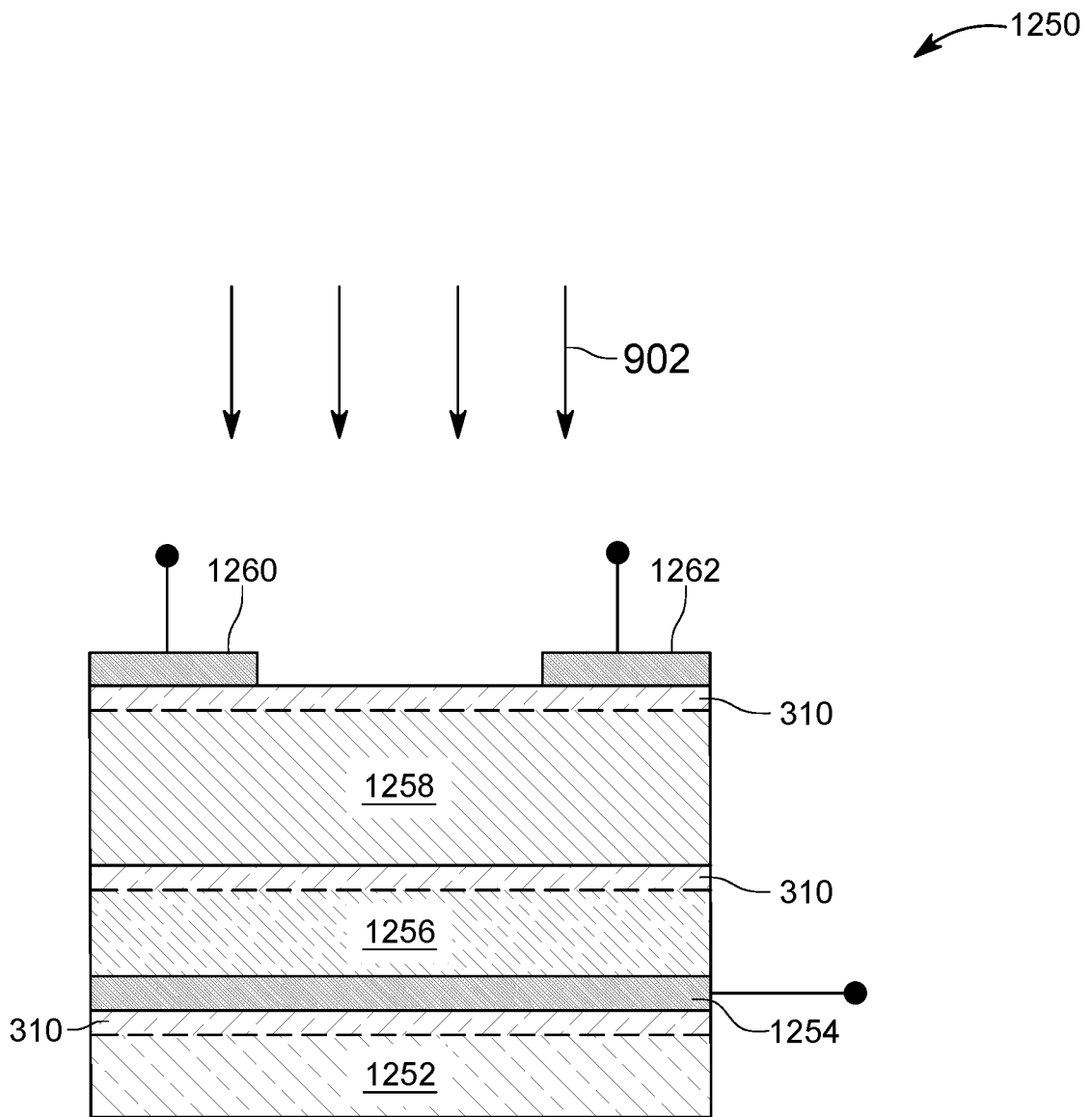


FIG. 12B

1300

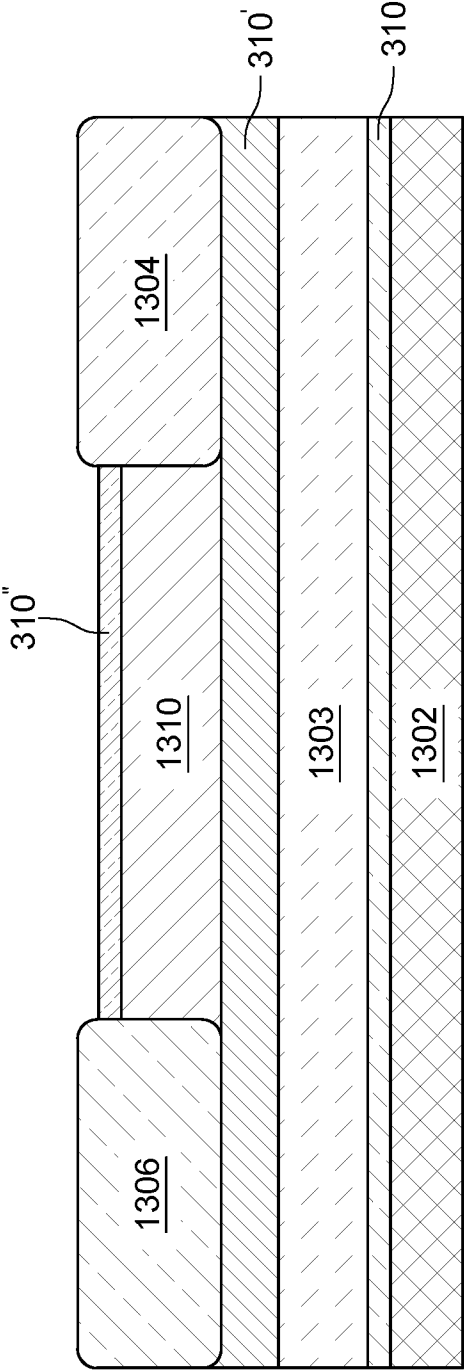


FIG. 13

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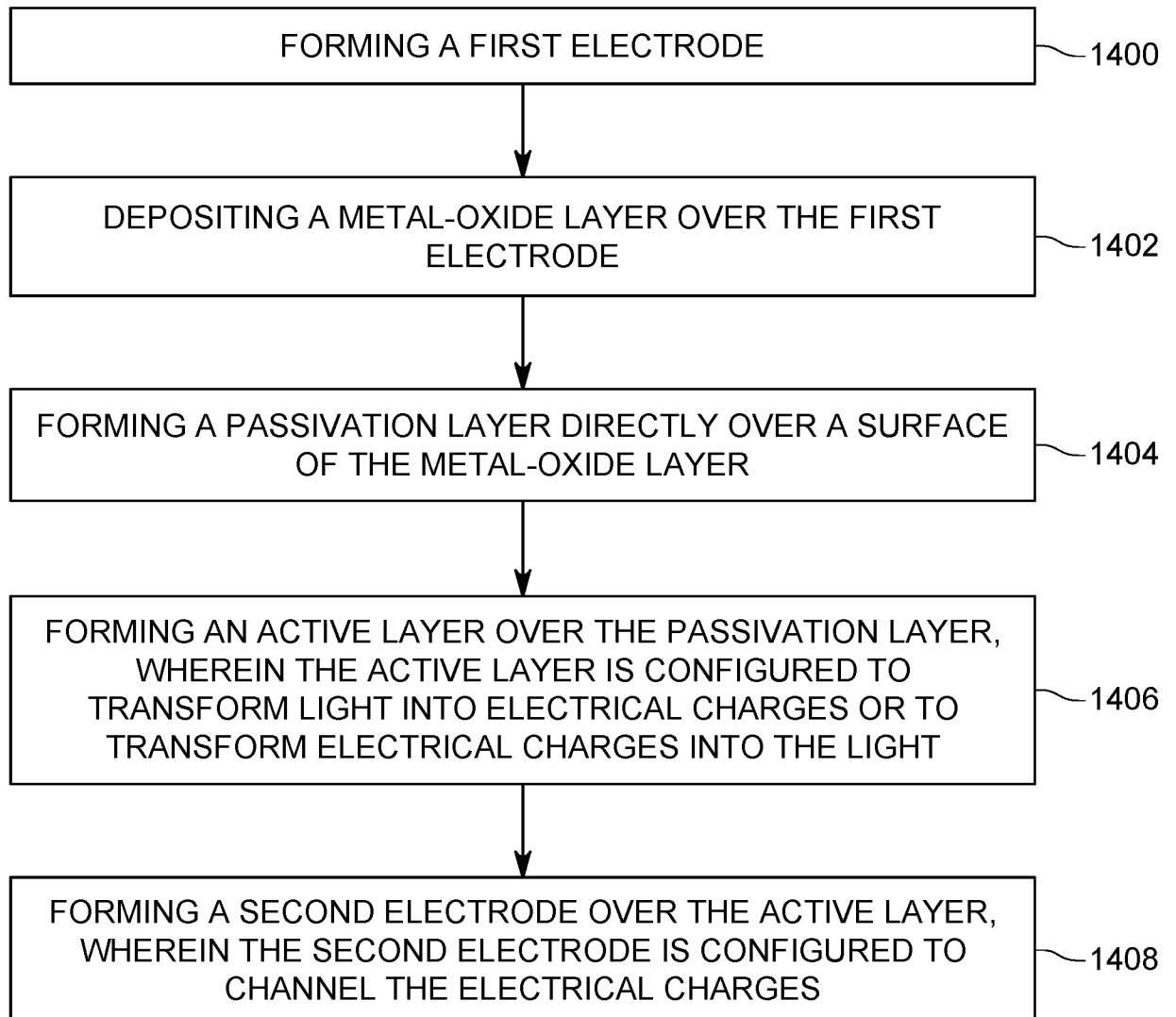


FIG. 14