DESCRIPTION

A METHOD AND APPARATUS FOR DETECTING INFRARED RADIATION WITH GAIN

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Provisional Patent Application Serial No. 61/503,317, filed June 30, 2011, the disclosure of which is hereby incorporated by reference in its entirety, including any figures, tables, or drawings.

BACKGROUND OF INVENTION

Infrared (IR) light is not visible to the human eye, but an IR photodetector can detect IR light. IR photodetectors have a wide range of potential applications, including night vision, range finding, security, and semiconductor wafer inspections. IR can refer to radiation having wavelengths longer than visible light (>0.7 μm) up to about 14 μm.

BRIEF SUMMARY

Embodiments of the subject invention relate to a photodetector capable of producing gain (i.e., a photodetector with gain). The photodetector can be, for example, an infrared (IR) photodetector. That is, the photodetector can be sensitive to at least a portion of light in the IR region. Embodiments of the subject invention also pertain to an IR-to-visible upconversion device. The IR-to-visible upconversion device can include a photodetector and an organic light-emitting device (OLED).

In an embodiment, a photodetector with gain can include a first electrode, a light sensitizing layer on the first electrode, an electron blocking/tunneling layer on the light sensitizing layer, and a second electrode on the electron blocking/tunneling layer.

In another embodiment, a method of fabricating a photodetector with gain can include: forming a first electrode; forming a light sensitizing layer on the first electrode; forming an electron blocking/tunneling layer on the light sensitizing layer; and forming a second electrode on the electron blocking/tunneling layer.

In another embodiment, an IR-to-visible upconversion device can include a photodetector with gain and an OLED coupled to the photodetector with gain. The photodetector with gain can include a first electrode, a light sensitizing layer on the first

electrode, an electron blocking/tunneling layer on the light sensitizing layer, and a second electrode on the electron blocking/tunneling layer.

In another embodiment, a method of forming an IR-to-visible upconversion device can include: forming a photodetector with gain; forming an OLED; and coupling the OLED to the photodetector with gain. Forming the photodetector with gain can include: forming a first electrode; forming a light sensitizing layer on the first electrode; forming an electron blocking/tunneling layer on the light sensitizing layer; and forming a second electrode on the electron blocking/tunneling layer.

BRIEF DESCRIPTION OF DRAWINGS

Figure 1A shows an absorption spectrum of PbS nanocrystals which can be used as an IR sensitizing layer according to an embodiment of the subject invention.

Figure 1B shows a schematic perspective view of a photodetector according to an embodiment of the subject invention.

Figure 2A shows a schematic energy band diagram of a photodetector, according to an embodiment of the subject invention, under applied voltage in the dark.

Figure 2B shows a schematic energy band diagram of a photodetector, according to an embodiment of the subject invention, under applied voltage and IR irradiation.

Figure 3A shows a schematic energy band diagram of a photodetector according to an embodiment of the subject invention.

Figure 3B shows current vs. voltage characteristics for a photodetector according to an embodiment of the subject invention under dark and photo (1240 nm infrared illumination) conditions.

Figure 4A shows a plot of gain as a function of applied voltage for a photodetector according to an embodiment of the subject invention.

Figure 4B shows a plot of detectivity as a function of applied voltage on a photodetector according to an embodiment of the subject invention.

Figure 5A shows a schematic energy band diagram of an infrared-to-visible upconversion device according to an embodiment of the subject invention.

Figure 5B shows a schematic energy band diagram of an infrared-to-visible upconversion device according to an embodiment of the subject invention.

Figure 5C shows a schematic energy band diagram of an infrared-to-visible upconversion device according to an embodiment of the subject invention.

DETAILED DISCLOSURE

When the terms "on" or "over" are used herein, when referring to layers, regions, patterns, or structures, it is understood that the layer, region, pattern or structure can be directly on another layer or structure, or intervening layers, regions, patterns, or structures may also be present. When the terms "under" or "below" are used herein, when referring to layers, regions, patterns, or structures, it is understood that the layer, region, pattern or structure can be directly under the other layer or structure, or intervening layers, regions, patterns, or structures may also be present. When the term "directly on" is used herein, when referring to layers, regions, patterns, or structures, it is understood that the layer, region, pattern or structure is directly on another layer or structure, such that no intervening layers, regions, patterns, or structures are present.

When the term "about" is used herein, in conjunction with a numerical value, it is understood that the value can be in a range of 95% of the value to 105% of the value, i.e. the value can be +/- 5% of the stated value. For example, "about 1 kg" means from 0.95 kg to 1.05 kg.

When the term "sensitive" is used herein, in conjunction with describing a photodetector being sensitive to a certain type of light or to photons having a wavelength of a given value or within a given range, it is understood that the photodetector is capable of absorbing the light to which it is sensitive and generating a carrier. When the term "not sensitive" or "insensitive" is used herein, in conjunction with describing a photodetector not being sensitive or being insensitive to a certain type of light or to photons having a wavelength of a given value or within a given range, it is understood that the photodetector is not able to absorb the light to which it is not sensitive and generate a carrier from the absorption of the light.

Embodiments of the subject invention relate to a photodetector capable of producing gain (i.e., a photodetector with gain). The photodetector can be, for example, an infrared (IR) photodetector. That is, the photodetector can be sensitive to at least a portion of light in the IR region. In a specific embodiment, the photodetector is sensitive to at least a portion of the wavelength range from 0.7 μm to 14 μm, inclusive or non-inclusive. In certain embodiments, the photodetector can be sensitive to IR light and can be insensitive to visible light. For example, a light sensitizing layer of the photodetector can be insensitive to at least a portion of the wavelength range from 0.4 μm to 0.7 μm. In an embodiment, a light sensitizing layer

of the photodetector can be insensitive to the entire wavelength range from 0.4 μm to 0.7 μm, inclusive or non-inclusive.

Referring to Figure 1B, in an embodiment, a photodetector **10** can include a first electrode **30**, a light sensitizing layer **50**, an electron blocking/tunneling layer **60**, and a second electrode **70**. The photodetector **10** can also optionally include a substrate **20** and/or a hole blocking layer **40**. The substrate **20** can be, for example, a glass substrate. Though Figure 1B includes labels of certain materials for the various components, these are intended for demonstrative purposes only and embodiments of the subject invention are not limited thereto.

The first electrode **30** can be a cathode, and the second electrode **70** can be an anode. In an alternative embodiment, the first electrode **30** can be an anode, and the second electrode **70** can be a cathode. In certain embodiments, the first electrode **30** and/or the second electrode **70** can be transparent to at least a portion of visible and/or at least a portion of IR light, though embodiments are not limited thereto.

The first electrode **30** can include one or more of the following materials: indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO. In a particular embodiment, the first electrode **30** can be an ITO electrode. The second electrode **70** can include one or more of the following materials: ITO, IZO, ATO, AZO, silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO. In a particular embodiment, the second electrode **70** can be a silver electrode.

In certain embodiments, the photodetector **10** can be an IR photodetector and the light sensitizing layer **50** can be an IR sensitizing layer. That is, the IR sensitizing layer can be sensitive to at least a portion of light in the IR range. The light sensitizing layer **50** can include, for example, one or more of the following materials: PbS nanocrystals (quantum dots), PbSe nanocrystals (quantum dots), PCTDA, SnPc, SnPc:C60, AlPcCl, AlPcCl:C60, TiOPc, TiOPc:C60, PbSe, PbS, InAs, InGaAs, Si, Ge, and GaAs.

Figure 1A shows an absorption spectrum for PbS nanocrystals as a light sensitizing layer **50**. Referring to Figure 1A, the PbS nanocrystal light sensitizing layer shows absorbance in at least a portion of the IR region.

In an embodiment, the electron blocking/tunneling layer can be a 1,1-bis[(di-4-tolylamino)phenyl]cyclohexane (TAPC)/MoO_3 stack layer. The TAPC layer can have a

thickness of, for example, 0 nm to 100 nm. The MoO_3 layer can have a thickness of, for example, 0 nm to 100 nm.

In an embodiment, the photodetector can include a hole blocking layer, and the hole blocking layer can include one or more of the following materials: ZnO, naphthalene tetracarboxylic anhydride (NTCDA), 2,9-Dimethyl-4,7-diphenyl-1,10-phenanthroline (BCP), p-bis(triphenylsilyl)benzene (UGH2), 4,7-diphenyl-1,10-phenanthroline (BPhen), tris-(8-hydroxy quinoline) aluminum (Alq3), 3,5'-N,N'-dicarbazole-benzene (mCP), C60, tris[3-(3-pyridyl)-mesityl]borane (3TPYMB), and TiO_2.

In an exemplary embodiment, the photodetector can include a first electrode, light sensitizing layer on the first electrode, an electron blocking/tunneling layer on the light sensitizing layer, and a second electrode on the electron blocking/tunneling layer. The electron blocking/tunneling layer can be, for example, a TAPC/MoO_3 stack layer, and the TAPC/MoO_3 stack layer can be positioned such that the TAPC layer is in direct contact with the light sensitizing layer and the MoO_3 layer is in direct contact with the second electrode. The light sensitizing layer can be, for example, an IR sensitizing layer and can include, e.g., PbS quantum dots. In a further embodiment, the photodetector can include a hole blocking layer on the first electrode and under the light sensitizing layer.

Figures 2A and 2B demonstrate the operating principle of a photodetector according to an embodiment of the subject invention. Referring to Figure 2A, when a bias is applied in the dark (i.e., no visible and/or IR light), holes are blocked from the first electrode due to hole blocking layer, and electrons are blocked from second electrode due to the electron blocking layer. Referring to Figure 2B, when the photodetector is irradiated with light (e.g., IR light), the light sensitizing layer (e.g., an IR sensitizing layer) generates electron-hole pairs, and the electrons flow to the first electrode due to the applied bias. The holes are accumulated in bulk trap sites of the electron blocking/tunneling layer, and the accumulated holes reduce the barrier width of the electron blocking/tunneling layer. Thus, the electron tunneling from the second electrode to the light sensitizing layer is enhanced significantly, thus producing gain.

Figure 3A shows a schematic band diagram of a photodetector according to an embodiment of subject invention, and Figure 3B shows the dark and photo current density-voltage (J-V) characteristics for a photodetector according to an embodiment of the subject invention.

Figure 4A shows a plot of the gain versus the applied voltage for a photodetector according to the subject invention, and Figure 4B shows a plot of the detectivity versus the

applied voltage for a photodetector according to an embodiment of the subject invention. Referring to Figure 4A, a very high gain can be seen, including a gain of more than 150 at an applied bias of -20 V. Referring to Figure 4B, the detectivity is saturated to more than 5 x 10^{12} Jones at values of the applied voltage of less than -18 V.

According to embodiments of the subject invention, a photodetector exhibits gain at applied bias (i.e., it is a photodetector with gain). The photodetector can exhibit a gain of, for example, about 150 at an applied bias of -20 V. In various embodiments, the photodetector can exhibit a gain any of the following values or ranges: 2, about 2, at least 2, 3, about 3, at least 3, ... , 160, about 160, at least 160 (where the "..." represents each number between 3 and 160, "about" each number between 3 and 160, and "at least" each number between 3 and 160), or any range having a first endpoint of any number from 2 to 159 and a second endpoint of any number from 3 to 160. The gain values and ranges of the preceding sentence can be exhibited at any applied voltage value from -30 V to 30 V.

Referring to Figures 5A-5C, embodiments of the subject invention also pertain to an IR-to-visible upconversion device **500**. The IR-to-visible upconversion device **500** can include a photodetector **10** and a light-emitting device (LED) **200**. In many embodiments, the LED **200** can be an organic LED (OLED). The IR-to-visible upconversion device **500** can be an IR-to-visible upconversion device with gain, and the photodetector **10** can be a photodetector with gain. In specific embodiments, the IR-to-visible upconversion device can include a photodetector with gain, as illustrated in Figures 1A-1B, 2A-2B, 3A-3B, and 4A-4B and/or as described in connection with the photodetectors of Figures 1A-1B, 2A-2B, 3A-3B, and 4A-4B. The OLED **200** can include at least one electrode, a hole transporting layer (HTL), a light emitting layer (LEL), and an electron transporting layer (ETL).

At least one electrode of the OLED **200** can be transparent to at least a portion of visible light and/or at least a portion of IR light, though embodiments are not limited thereto. Each electrode of the OLED **200** can include one or more of the following materials: ITO, IZO, ATO, AZO, silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, $CsCO_3$/ITO, and a Mg:Ag/Alq3 stack layer, though embodiments are not limited thereto. The HTL of the OLED **200** can include one or more of the following materials: NPD, TAPC, TFB, TPD, and diamine derivative, though embodiments are not limited thereto. The LEL of the OLED **200** can include one or more of the following materials: Iridium tris(2-phenylpyidine) (Ir(ppy)3), [2-methoxy-5-(2-ethylhexyloxy)-p-phenylenevinylene] (MEH-PPV), Tris-(8-quinolinolato) aluminum) (Alq3),

and bis[(4,6-di-fluorophenyl)-pyridinate-]picolinate (Flrpic), though embodiments are not limited thereto. The ETL of the OLED **200** can include one or more of the following materials: BCP, Bphen, 3TPYMB, and Alq3, though embodiments are not limited thereto.

In a particular embodiment, the electrode of the OLED **200** is a Mg:Ag/Alq3 stack layer. The Mg:Ag layer of the Mg:Ag/Alq3 stack layer can have a composition of, for example, Mg:Ag (10:1) and can have a thickness of, for example, less than 30nm. The Alq3 layer of the Mg:Ag/Alq3 stack layer can have a thickness of, for example, from 0 nm to 200 nm.

The photodetector **10** can be a photodetector with gain as described herein, though only one electrode need be present. That is, the photodetector **10** can include at least one electrode, a light sensitizing layer, and an electron blocking/tunneling layer. The photodetector **10** can also optionally include a substrate and/or a hole blocking layer.

The electrode can include one or more of the following materials: ITO, IZO, ATO, AZO, silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

In certain embodiments, the photodetector **10** can be an IR photodetector and the light sensitizing layer can be an IR sensitizing layer. The light sensitizing layer can include, for example, one or more of the following materials: PbS nanocrystals (quantum dots), PbSe nanocrystals (quantum dots), PCTDA, SnPc, SnPc:C60, AlPcCl, AlPcCl:C60, TiOPc, TiOPc:C60, PbSe, PbS, InAs, InGaAs, Si, Ge, and GaAs.

In an embodiment, the electron blocking/tunneling layer can be a TAPC/MoO_3 stack layer. The TAPC layer can have a thickness of, for example, 0 nm to 100 nm. The MoO_3 layer can have a thickness of, for example, 0 nm to 100 nm.

In an embodiment, the photodetector can include a hole blocking layer, and the hole blocking layer can include one or more of the following materials: ZnO, NTCDA, BCP, UGH2, BPhen, Alq3, mCP, 3TPYMB, and TiO_2.

Referring to Figure 5A, in a further embodiment, the IR-to-visible upconversion device **500** can also include an interconnecting part **100** between the photodetector **10** and the OLED **200**. The interconnecting part **100** can be positioned such that the electron blocking/tunneling layer of the photodetector **10** is closer than the light sensitizing layer is to the interconnecting part **100**, and the HTL of the OLED **200** is closer than the ETL is to the interconnecting part **100**. The photodetector **10** can include an electrode under the light

sensitizing layer, and that electrode can be an anode. The OLED **200** can include an electrode on the ETL, and that electrode can be a cathode.

In an embodiment, the interconnecting part **100** can include an HBL **110** and an EBL **120**. The lowest unoccupied molecular orbital (LUMO) of the HBL **110** of the interconnecting part **100** can be close to the highest occupied molecular orbital (HOMO) of the EBL **120** of the interconnecting part **100**. Thus, when a bias is applied, electrons and holes can be generated in the interconnecting part **100**. In an embodiment, the LUMO of the HBL **110** of the interconnecting part **100** and the HOMO of the EBL **120** of the interconnecting part **100** can be no more than 1 eV apart. In a further embodiment, the LUMO of the IIBL **110** of the interconnccting part **100** and the HOMO of the EBL **120** of the interconnecting part **100** can be no more than 0.5 eV apart. That is, the energy difference between the HOMO of the EBL **120** of the interconnecting part **100** and the LUMO of the HBL **110** of the interconnecting part **100** can be 0.5 eV or less. The interconnecting part **100** can be positioned within the IR-to-visible upconversion device **500** such that the HBL **120** of the interconnecting part **100** can be adjacent to the photodetector **10** and the EBL **120** of the interconnecting part **100** can be adjacent to the OLED **200**. In embodiment, the photodetector **10** can include a second electrode **70** on its EBL/tunneling layer, and the HBL **120** of the interconnecting part **100** can be in direct contact with the second electrode **70** of the photodetector **10**. The second electrode **70** of the photodetector **10** can be a cathode. The second electrode **70** of the photodetector **10** can include one or more of the following materials: ITO, IZO, ATO, AZO, silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO. In a particular embodiment, the second electrode **70** of the photodetector **10** can be a silver electrode. Though the dotted line around the interconnecting part **100** in Figure 5A extends beyond the HBL **110** and the EBL **120**, the interconnecting part does not necessarily include any additional components beyond the HBL **110** and the EBL **120**. In certain embodiments, additional components may be present (e.g., one or more electrodes or substrates).

Referring again to Figures 5B and 5C, in an embodiment, the IR-to-visible upconversion device **500** does not include an interconnecting part **100**, and the photodetector **10** is positioned directly adjacent to the OLED **200**. The OLED **200** can be positioned such that the ETL of the OLED **200** is closer to the light sensitizing layer of the photodetector **10** than it is to the electron blocking/tunneling layer of the photodetector **10**. In a particular embodiment, the photodetector can include a hole blocking layer adjacent to the light

sensitizing layer, and the ETL of the OLED **200** can be positioned adjacent to and in contact with the hole blocking layer of the photodetector **10**. The photodetector **10** can include an electrode adjacent to and in contact with the electron blocking/tunneling layer, and the OLED **200** can include an electrode adjacent to and in contact with the HTL. The electrode of the photodetector **10** can be, for example, a cathode, and the electrode of the OLED **200** can be, for example, an anode.

In the IR-to-visible upconversion devices **500** shown in Figures 5A-5C, a substrate (not shown) can also be present. In many embodiments, the IR-to-visible upconversion device **500** can be flipped or turned around and still function properly. For example, the substrate can be adjacent to the anode in Figure 5B and adjacent to the cathode in Figure 5C, such that Figure 5B shows a similar configuration to that of Figure 5C but with the IR-to-visible upconversion device **500** turned around on the substrate. In the IR-to-visible upconversion device **500** depicted in Figure 5A, the substrate can be adjacent to the anode or the cathode. In a particular embodiment, an IR-to-visible upconversion device **500** can include an interconnecting part **100** (as shown in Figure 5A), and the substrate can be adjacent to the anode. IR light can be incident on the IR-to-visible upconversion device **500** from any direction, and visible light can be emitted from the IR-to-visible upconversion device **500** in any direction. The OLED **200** can be transparent to at least a portion of light in the IR spectrum, though embodiments are not limited thereto. The photodetector **10** can be transparent to at least a portion of light in the visible spectrum, though embodiments are not limited thereto.

Referring again to Figures 5A-5C, the IR-to-visible upconversion device **500** functions by emitting visible light from the OLED **200** when the photodetector **10** absorbs IR light. That is, the light sensitizing layer (e.g., an IR sensitizing layer) of the photodetector **10** absorbs IR light, causing carriers to flow. The carriers flow to the OLED **200**, either directly or via an interconnecting part **100**, causing the LEL of the OLED **200** to emit visible light. The IR-to-visible upconversion device **500** can include a photodetector **10** with gain and can advantageously exhibit gain.

Embodiments of the subject invention also relate to methods of fabricating a photodetector with gain. The photodetector can be, for example, an IR photodetector. In an embodiment, a method of fabricating a photodetector with gain can include: forming a light sensitizing layer on a first electrode, forming an electron blocking/tunneling layer on the light sensitizing layer, and forming a second electrode on the electron blocking/tunneling layer.

The method can also optionally include forming the first electrode on a substrate and/or forming a hole blocking layer on the first electrode such that the light sensitizing layer is formed on the hole blocking layer. The substrate can be, for example, a glass substrate.

The first electrode can be a cathode, and the second electrode can be an anode. In an alternative embodiment, the first electrode can be an anode, and the second electrode can be a cathode. In certain embodiments, the first electrode and/or the second electrode can be transparent to at least a portion of visible and/or at least a portion of IR light, though embodiments are not limited thereto.

The first electrode can include one or more of the following materials: indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO. The second electrode can include one or more of the following materials: ITO, IZO, ATO, AZO, silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

In certain embodiments, the photodetector can be an IR photodetector and the light sensitizing layer can be an IR sensitizing layer. The light sensitizing layer can include, for example, one or more of the following materials: PbS nanocrystals (quantum dots), PbSe nanocrystals (quantum dots), PCTDA, SnPc, SnPc:C60, AlPcCl, AlPcCl:C60, TiOPc, TiOPc:C60, PbSe, PbS, InAs, InGaAs, Si, Ge, and GaAs.

In an embodiment, the electron blocking/tunneling layer can be a TAPC/MoO_3 stack layer. The TAPC layer can be formed to a thickness of, for example, 0 nm to 100 nm. The MoO_3 layer can be formed to a thickness of, for example, 0 nm to 100 nm.

In an embodiment, the method can include forming a hole blocking layer, and the hole blocking layer can include one or more of the following materials: ZnO, NTCDA, BCP, UGH2, BPhen, Alq3, 3mCP, 3TPYMB, and TiO_2.

In a particular embodiment, the method of fabricating a photodetector can include: forming a light sensitizing layer on a first electrode, forming an electron blocking/tunneling layer on the light sensitizing layer, and forming a second electrode on the electron blocking/tunneling layer. The electron blocking/tunneling layer can be, for example, a TAPC/MoO_3 stack layer, and the TAPC/MoO_3 stack layer can be formed such that the TAPC layer is formed directly on and in contact with the light sensitizing layer and the MoO_3 layer is formed directly on and in contact with the TAPC layer. The second electrode can then be formed directly on and in contact with the MoO_3 layer of the TAPC/MoO_3 stack layer. The

light sensitizing layer can be, for example, an IR sensitizing layer and can include, e.g., PbS quantum dots. In a further embodiment, the method can include forming a hole blocking layer on the first electrode such that the light sensitizing layer is formed directly on and in contact with the hole blocking layer.

Embodiments of the subject invention also relate to methods of detecting radiation using a photodetector with gain. The photodetector can be, for example, an IR photodetector such that the method can detect IR radiation. In an embodiment, a method of using a photodetector with gain to detect radiation can include: providing a photodetector with gain, wherein the photodetector includes a first electrode, a light sensitizing layer, an electron blocking/tunneling layer, and a second electrode. The photodetector can also optionally include a substrate and/or a hole blocking layer. The substrate can be, for example, a glass substrate.

The first electrode can be a cathode, and the second electrode can be an anode. In an alternative embodiment, the first electrode can be an anode, and the second electrode can be a cathode. In certain embodiments, the first electrode and/or the second electrode can be a transparent electrode.

The first electrode can include one or more of the following materials: indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO. The second electrode can include one or more of the following materials: ITO, IZO, ATO, AZO, silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

In certain embodiments, the photodetector can be an IR photodetector and the light sensitizing layer can be an IR sensitizing layer. The light sensitizing layer can include, for example, one or more of the following materials: PbS nanocrystals (quantum dots), PbSe nanocrystals (quantum dots), PCTDA, SnPc, SnPc:C60, AlPcCl, AlPcCl:C60, TiOPc, TiOPc:C60, PbSe, PbS, InAs, InGaAs, Si, Ge, and GaAs.

In an embodiment, the electron blocking/tunneling layer can be a TAPC/MoO_3 stack layer. The TAPC layer can be formed to a thickness of, for example, 0 nm to 100 nm. The MoO_3 layer can be formed to a thickness of, for example, 0 nm to 100 nm.

In an embodiment, the photodetector can include a hole blocking layer, and the hole blocking layer can include one or more of the following materials: ZnO, NTCDA, BCP, UGH2, BPhen, Alq3, 3mCP, 3TPYMB, and TiO_2.

In a particular embodiment, the photodetector can include: a light sensitizing layer on a first electrode, an electron blocking/tunneling layer on the light sensitizing layer, and a second electrode on the electron blocking/tunneling layer. The electron blocking/tunneling layer can be, for example, a TAPC/MoO_3 stack layer, and the TAPC/MoO_3 stack layer can be positioned such that the TAPC layer is directly on and in contact with the light sensitizing layer and the MoO_3 layer is directly on and in contact with the TAPC layer. The second electrode can then be directly on and in contact with the MoO_3 layer of the TAPC/MoO_3 stack layer. The light sensitizing layer can be, for example, an IR sensitizing layer and can include, e.g., PbS quantum dots. In a further embodiment, the photodetector can include a hole blocking layer on the first electrode and under the light sensitizing layer.

Embodiments of the subject invention also relate to methods of forming an IR-to-visible upconversion device. The IR-to-visible upconversion device can be an IR-to-visible upconversion device with gain, and the photodetector can be a photodetector with gain. In an embodiment, a method of fabricating an IR-to-visible upconversion device can include: forming a photodetector with gain; forming an LED; and coupling the LED and the photodetector with gain. The LED can be an OLED. Forming the OLED can include: forming at least one electrode, forming a hole transporting layer (HTL), forming a light emitting layer (LEL), and forming an electron transporting layer (ETL).

At least one electrode of the OLED can be transparent to at least a portion of visible and/or at least a portion of IR light, though embodiments are not limited thereto. Each electrode of the OLED can include one or more of the following materials: ITO, IZO, ATO, AZO, silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, $CsCO_3$/ITO, and a Mg:Ag/Alq3 stack layer, though embodiments are not limited thereto. The HTL of the OLED can include one or more of the following materials: NPD, TAPC, TFB, TPD, and diamine derivative, though embodiments are not limited thereto. The LEL of the OLED can include one or more of the following materials: Ir(ppy)3, MEH-PPV, Alq3, and Flrpic, though embodiments are not limited thereto. The ETL of the OLED can include one or more of the following materials: BCP, Bphen, 3TPYMB, and Alq3, though embodiments are not limited thereto.

In a particular embodiment, the electrode of the OLED is a Mg:Ag/Alq3 stack layer. The Mg:Ag layer of the Mg:Ag/Alq3 stack layer can have a composition of, for example, Mg:Ag (10:1) and can be formed to a thickness of, for example, less than 30nm. The Alq3

layer of the Mg:Ag/Alq3 stack layer can be formed to a thickness of, for example, from 0 nm to 200 nm.

The photodetector can be a photodetector with gain and can be formed as described herein, though only one electrode need be formed. That is, forming the photodetector can include forming at least one electrode, forming a light sensitizing layer, and forming an electron blocking/tunneling layer. Forming the photodetector can also optionally include proving a substrate and/or forming a hole blocking layer.

The electrode can be formed of one or more of the following materials: ITO, IZO, ATO, AZO, silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

In certain embodiments, the photodetector can be an IR photodetector and the light sensitizing layer can be an IR sensitizing layer. The light sensitizing layer can be formed of, for example, one or more of the following materials: PbS nanocrystals (quantum dots), PbSe nanocrystals (quantum dots), PCTDA, SnPc, SnPc:C60, AlPcCl, AlPcCl:C60, TiOPc, TiOPc:C60, PbSe, PbS, InAs, InGaAs, Si, Ge, and GaAs.

In an embodiment, the electron blocking/tunneling layer can be a TAPC/MoO_3 stack layer. The TAPC layer can be formed to a thickness of, for example, 0 nm to 100 nm. The MoO_3 layer can be formed to a thickness of, for example, 0 nm to 100 nm.

In an embodiment, forming the photodetector can include forming a hole blocking layer, and the hole blocking layer can include one or more of the following materials: ZnO, NTCDA, BCP, UGH2, BPhen, Alq3, mCP, 3TPYMB, and TiO_2.

In a further embodiment, coupling the photodetector with gain to the OLED can include coupling the photodetector with gain to an interconnecting part and coupling the OLED to the interconnecting part. The photodetector can be coupled to the interconnecting part such that the electron blocking/tunneling layer of the photodetector is closer than the light sensitizing layer is to the interconnecting part. The OLED can be coupled to the interconnecting part such that the HTL of the OLED is closer than the ETL is to the interconnecting part. The photodetector can include an electrode under the light sensitizing layer, and that electrode can be an anode. The OLED can include an electrode on the ETL, and that electrode can be a cathode.

In an embodiment, coupling the photodetector with gain to the OLED can include coupling the photodetector with gain directly to the OLED. The photodetector with gain can be coupled to the OLED such that the ETL of the OLED is closer to the light sensitizing layer

of the photodetector than it is to the electron blocking/tunneling layer of the photodetector. In a particular embodiment, the photodetector can include a hole blocking layer adjacent to the light sensitizing layer, and the photodetector with gain can be coupled to the OLED such that the ETL of the OLED is adjacent to and in contact with the hole blocking layer of the photodetector. The photodetector can include an electrode adjacent to and in contact with the electron blocking/tunneling layer, and the OLED can include an electrode adjacent to and in contact with the HTL. The electrode of the photodetector can be, for example, a cathode, and the electrode of the OLED can be, for example, an anode.

Embodiments of the subject invention also relate to methods of upconverting IR radiation to visible radiation using an IR-to-visible upconversion device. The IR-to-visible upconversion device can include a photodetector and an LED. The LED can be an OLED. The IR-to-visible upconversion device can be an IR-to-visible upconversion device with gain, and the photodetector can be a photodetector with gain. The OLED can include at least one electrode, a hole transporting layer (HTL), a light emitting layer (LEL), and an electron transporting layer (ETL).

At least one electrode of the OLED can be transparent to at least a portion of visible and/or at least a portion of IR light, though embodiments are not limited thereto. Each electrode of the OLED can include one or more of the following materials: ITO, IZO, ATO, AZO, silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, $CsCO_3$/ITO, and a Mg:Ag/Alq3 stack layer, though embodiments are not limited thereto. The HTL of the OLED can include one or more of the following materials: NPD, TAPC, TFB, TPD, and diamine derivative, though embodiments are not limited thereto. The LEL of the OLED can include one or more of the following materials: Ir(ppy)3, MEH-PPV, Alq3, and Flrpic, though embodiments are not limited thereto. The ETL of the OLED can include one or more of the following materials: BCP, Bphen, 3TPYMB, and Alq3, though embodiments are not limited thereto.

In a particular embodiment, the electrode of the OLED is a Mg:Ag/Alq3 stack layer. The Mg:Ag layer of the Mg:Ag/Alq3 stack layer can have a composition of, for example, Mg:Ag (10:1) and can have a thickness of, for example, less than 30nm. The Alq3 layer of the Mg:Ag/Alq3 stack layer can have a thickness of, for example, from 0 nm to 200 nm.

The photodetector can be a photodetector with gain as described herein, though only one electrode need be present. That is, the photodetector can include at least one electrode, a

light sensitizing layer, and an electron blocking/tunneling layer. The photodetector can also optionally include a substrate and/or a hole blocking layer.

The electrode can include one or more of the following materials: ITO, IZO, ATO, AZO, silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

In certain embodiments, the photodetector can be an IR photodetector and the light sensitizing layer can be an IR sensitizing layer. The light sensitizing layer can include, for example, one or more of the following materials: PbS nanocrystals (quantum dots), PbSe nanocrystals (quantum dots), PCTDA, SnPc, SnPc:C60, AlPcCl, AlPcCl:C60, TiOPc, TiOPc:C60, PbSe, PbS, InAs, InGaAs, Si, Gc, and GaAs.

In an embodiment, the electron blocking/tunneling layer can be a TAPC/MoO_3 stack layer. The TAPC layer can have a thickness of, for example, 0 nm to 100 nm. The MoO_3 layer can have a thickness of, for example, 0 nm to 100 nm.

In an embodiment, the photodetector can include a hole blocking layer, and the hole blocking layer can include one or more of the following materials: ZnO, NTCDA, BCP, UGH2, BPhen, Alq3, mCP, 3TPYMB, and TiO_2.

In a further embodiment, the IR-to-visible upconversion device can also include an interconnecting part between the photodetector and the OLED. The interconnecting part can be positioned such that the electron blocking/tunneling layer of the photodetector is closer than the light sensitizing layer is to the interconnecting part, and the HTL of the OLED is closer than the ETL is to the interconnecting part. The photodetector can include an electrode under the light sensitizing layer, and that electrode can be an anode. The OLED can include an electrode on the ETL, and that electrode can be a cathode.

In an embodiment, the IR-to-visible upconversion device does not include an interconnecting part, and the photodetector is positioned directly adjacent to the OLED. The OLED can be positioned such that the ETL of the OLED is closer to the light sensitizing layer of the photodetector than it is to the electron blocking/tunneling layer of the photodetector. In a particular embodiment, the photodetector can include a hole blocking layer adjacent to the light sensitizing layer, and the ETL of the OLED can be positioned adjacent to and in contact with the hole blocking layer of the photodetector. The photodetector can include an electrode adjacent to and in contact with the electron blocking/tunneling layer, and the OLED can include an electrode adjacent to and in contact

with the HTL. The electrode of the photodetector can be, for example, a cathode, and the electrode of the OLED can be, for example, an anode.

In many embodiments, the IR-to-visible upconversion device can be flipped or turned around and still function properly. The OLED can be transparent to at least a portion of light in the IR spectrum, though embodiments are not limited thereto. The photodetector can be transparent to at least a portion of light in the visible spectrum, though embodiments are not limited thereto.

The IR-to-visible upconversion device upconverts IR light to visible light. The IR-to-visible upconversion emits visible light from the OLED when the photodetector absorbs IR light. That is, the light sensitizing layer (e.g., an IR sensitizing layer) of the photodetector absorbs IR light, causing carriers to flow. The carriers flow to the OLED, either directly or via an interconnecting part, causing the LEL of the OLED to emit visible light. The IR-to-visible upconversion device can include a photodetector with gain and can advantageously exhibit gain.

EXAMPLE 1

A photodetector was fabricated on a glass substrate. The photodetector included an ITO first electrode, a ZnO hole blocking layer on the first electrode, a PbS quantum dot light sensitizing layer on the hole blocking layer, a TAPC/MoO_3 stack electron blocking/tunneling layer on the light sensitizing layer, and a second electrode on the electron blocking/tunneling layer. The PbS quantum dot light sensitizing layer had the absorbance spectrum shown in Figure 1A. The photodetector displayed the J-V characteristic curves (for dark and IR illumination at 1240 nm and 0.302 W/cm_2) shown in Figure 3B. Additionally, the photodetector exhibited the gain and detectivity, as functions of applied voltage, shown in Figures 4A and 4B, respectively.

All patents, patent applications, provisional applications, and publications referred to or cited herein are incorporated by reference in their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

CLAIMS

What is claimed is:

1. A photodetector with gain, comprising:
a first electrode;
a light sensitizing layer on the first electrode;
an electron blocking/tunneling layer on the light sensitizing layer; and
a second electrode on the electron blocking/tunneling layer.

2. The photodetector with gain according to claim 1, wherein the light sensitizing layer is sensitive to photons having a wavelength in a range of from 0.7 μm to 14 μm, inclusive.

3. The photodetector with gain according to claim 2, wherein the light sensitizing layer is insensitive to photons having a wavelength of at least 0.4 μm and less than 0.7 μm.

4. The photodetector with gain according to claim 1, wherein the light sensitizing layer comprises PbS quantum dots or PbSe quantum dots.

5. The photodetector with gain according to claim 1, wherein the light sensitizing layer comprises PbS quantum dots.

6. The photodetector with gain according to claim 1, wherein the light sensitizing layer comprises at least one material selected from the group consisting of PbS quantum dots, PbSe quantum dots, PCTDA, SnPc, SnPc:C60, AlPcCl, AlPcCl:C60, TiOPc, TiOPc:C60, PbSe, PbS, InAs, InGaAs, Si, Ge, and GaAs.

7. The photodetector with gain according to claim 1, wherein the first electrode comprises at least one material selected from the group consisting of indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver,

calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

8. The photodetector with gain according to claim 1, wherein the second electrode comprises at least one material selected from the group consisting of indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

9. The photodetector with gain according to claim 1, wherein the first electrode is an anode, and wherein the second electrode is a cathode.

10. The photodetector with gain according to claim 9, wherein the first electrode comprises at least one material selected from the group consisting of indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO; and wherein the second electrode comprises at least one material selected from the group consisting of indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

11. The photodetector with gain according to claim 1, wherein the electron blocking/tunneling layer is a 1,1-bis[(di-4-tolylamino)phenyl]cyclohexane (TAPC)/MoO_3 stack layer.

12. The photodetector with gain according to claim 11, wherein the TAPC layer is in direct contact with the light sensitizing layer, and wherein the MoO_3 layer is in direct contact with the second electrode.

13. The photodetector with gain according to claim 11, wherein the TAPC layer has a thickness of no more than 100 nm, and wherein the MoO_3 layer has a thickness of no more than 100 nm.

14. The photodetector with gain according to claim 1, further comprising a hole blocking layer on the first electrode and under the light sensitizing layer.

15. The photodetector with gain according to claim 14, wherein the hole blocking layer comprises at least one material selected from the group consisting of ZnO, naphthalene tetracarboxylic anhydride (NTCDA), 2,9-Dimethyl-4,7-diphenyl-1,10-phenanthroline (BCP), p-bis(triphenylsilyl)benzene (UGH2), 4,7-diphenyl-1,10-phenanthroline (BPhen), tris-(8-hydroxy quinoline) aluminum (Alq3), 3,5'-N,N'-dicarbazole-benzene (mCP), C60, tris[3-(3-pyridyl)-mesityl]borane (3TPYMB), and TiO_2.

16. The photodetector with gain according to claim 1, further comprising a glass substrate under the first electrode.

17. The photodetector with gain according to claim 1,
wherein the electron blocking/tunneling layer is a TAPC/MoO_3 stack layer,
wherein the TAPC layer is in direct contact with the light sensitizing layer,
wherein the MoO_3 layer is in direct contact with the second electrode, and
wherein the light sensitizing layer comprises PbS quantum dots.

18. The photodetector with gain according to claim 17, further comprising a hole blocking layer on the first electrode and under the light sensitizing layer.

19. A method of fabricating a photodetector with gain, comprising:
forming a first electrode;
forming a light sensitizing layer on the first electrode;
forming an electron blocking/tunneling layer on the light sensitizing layer; and
forming a second electrode on the electron blocking/tunneling layer.

20. The method according to claim 19, wherein the light sensitizing layer is sensitive to photons having a wavelength in a range of from 0.7 μm to 14 μm, inclusive.

21. The method according to claim 20, wherein the light sensitizing layer is insensitive to photons having a wavelength of at least 0.4 μm and less than 0.7 μm.

22. The method according to claim 19, wherein the light sensitizing layer comprises PbS quantum dots or PbSe quantum dots.

23. The method according to claim 19, wherein the light sensitizing layer comprises PbS quantum dots.

24. The method according to claim 19, wherein the light sensitizing layer comprises at least one material selected from the group consisting of PbS quantum dots, PbSe quantum dots, PCTDA, SnPc, SnPc:C60, AlPcCl, AlPcCl:C60, TiOPc, TiOPc:C60, PbSe, PbS, InAs, InGaAs, Si, Ge, and GaAs.

25. The method according to claim 19, wherein the first electrode comprises at least one material selected from the group consisting of indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

26. The method according to claim 19, wherein the second electrode comprises at least one material selected from the group consisting of indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

27. The method according to claim 19, wherein the first electrode is an anode, and wherein the second electrode is a cathode.

28. The method according to claim 27, wherein the first electrode comprises at least one material selected from the group consisting of indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium,

magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO; and wherein the second electrode comprises at least one material selected from the group consisting of indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

29. The method according to claim 19, wherein forming the electron blocking/tunneling layer comprises forming a TAPC/MoO_3 stack layer.

30. The method according to claim 29, wherein the TAPC layer is formed in direct contact with the light sensitizing layer, and wherein the second electrode is formed in direct contact with the MoO_3 layer.

31. The method according to claim 29, wherein the TAPC layer has a thickness of no more than 100 nm, and wherein the MoO_3 layer has a thickness of no more than 100 nm.

32. The method according to claim 19, further comprising forming a hole blocking layer on the first electrode, wherein the light sensitizing layer is formed on the hole blocking layer.

33. The method according to claim 32, wherein the hole blocking layer comprises at least one material selected from the group consisting of ZnO, naphthalene tetracarboxylic anhydride (NTCDA), 2,9-Dimethyl-4,7-diphenyl-1,10-phenanthroline (BCP), p-bis(triphenylsilyl)benzene (UGH2), 4,7-diphenyl-1,10-phenanthroline (BPhen), tris-(8-hydroxy quinoline) aluminum (Alq3), 3,5'-N,N'-dicarbazole-benzene (mCP), C60, tris[3-(3-pyridyl)-mesityl]borane (3TPYMB), and TiO_2.

34. The method according to claim 19, wherein forming the first electrode comprises forming the first electrode on a glass substrate.

35. The method according to claim 19,

wherein forming the electron blocking/tunneling layer comprises forming a TAPC/MoO_3 stack layer,

wherein the TAPC layer is formed in direct contact with the light sensitizing layer,

wherein the second electrode is formed in direct contact with the MoO_3 layer, and

wherein the light sensitizing layer comprises PbS quantum dots.

36. The method according to claim 35, further comprising forming a hole blocking layer on the first electrode, wherein the light sensitizing layer is formed on the hole blocking layer.

37. An infrared (IR)-to-visible upconversion device, comprising:

a photodetector with gain; and

an organic light-emitting device (OLED) coupled to the photodetector with gain,

wherein the photodetector with gain comprises:

a first photodetector electrode;

a light sensitizing layer on the first photodetector electrode;

an electron blocking/tunneling layer on the light sensitizing layer; and

a second photodetector electrode on the electron blocking/tunneling layer.

38. The IR-to-visible upconversion device according to claim 37, wherein the light sensitizing layer is sensitive to photons having a wavelength in a range of from 0.7 μm to 14 μm, inclusive.

39. The IR-to-visible upconversion device according to claim 38, wherein the light sensitizing layer is insensitive to photons having a wavelength of at least 0.4 μm and less than 0.7 μm.

40. The IR-to-visible upconversion device according to claim 37, wherein the light sensitizing layer comprises PbS quantum dots or PbSe quantum dots.

41. The IR-to-visible upconversion device according to claim 37, wherein the light sensitizing layer comprises PbS quantum dots.

42. The IR-to-visible upconversion device according to claim 37, wherein the light sensitizing layer comprises at least one material selected from the group consisting of PbS quantum dots, PbSe quantum dots, PCTDA, SnPc, SnPc:C60, AlPcCl, AlPcCl:C60, TiOPc, TiOPc:C60, PbSe, PbS, InAs, InGaAs, Si, Ge, and GaAs.

43. The IR-to-visible upconversion device according to claim 37, wherein the first photodetector electrode comprises at least one material selected from the group consisting of indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

44. The IR-to-visible upconversion device according to claim 37, wherein the second photodetector electrode comprises at least one material selected from the group consisting of indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

45. The IR-to-visible upconversion device according to claim 37, wherein the first photodetector electrode is an anode, and wherein the second photodetector electrode is a cathode.

46. The IR-to-visible upconversion device according to claim 45, wherein the first photodetector electrode comprises at least one material selected from the group consisting of indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO; and wherein the second photodetector electrode comprises at least one material selected from the group consisting of indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide

(AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

47. The IR-to-visible upconversion device according to claim 37, wherein the electron blocking/tunneling layer is a TAPC/MoO_3 stack layer.

48. The IR-to-visible upconversion device according to claim 47, wherein the TAPC layer is in direct contact with the light sensitizing layer, and wherein the MoO_3 layer is in direct contact with the second photodetector electrode.

49. The IR-to-visible upconversion device according to claim 47, wherein the TAPC layer has a thickness of no more than 100 nm, and wherein the MoO_3 layer has a thickness of no more than 100 nm.

50. The IR-to-visible upconversion device according to claim 37, further comprising a hole blocking layer on the first photodetector electrode and under the light sensitizing layer.

51. The IR-to-visible upconversion device according to claim 50, wherein the hole blocking layer comprises at least one material selected from the group consisting of ZnO, naphthalene tetracarboxylic anhydride (NTCDA), 2,9-Dimethyl-4,7-diphenyl-1,10-phenanthroline (BCP), p-bis(triphenylsilyl)benzene (UGH2), 4,7-diphenyl-1,10-phenanthroline (BPhen), tris-(8-hydroxy quinoline) aluminum (Alq3), 3,5'-N,N'-dicarbazole-benzene (mCP), C60, tris[3-(3-pyridyl)-mesityl]borane (3TPYMB), and TiO_2.

52. The IR-to-visible upconversion device according to claim 37, wherein the OLED comprises an OLED electrode, a hole transporting layer (HTL), a light emitting layer (LEL), and an electron transporting layer (ETL).

53. The IR-to-visible upconversion device according to claim 52, wherein the OLED electrode comprises at least one material selected from the group consisting of ITO,

IZO, ATO, AZO, silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, $CsCO_3$/ITO, and a Mg:Ag/Alq3 stack layer.

54. The IR-to-visible upconversion device according to claim 52, wherein the HTL comprises at least one material selected from the group consisting of NPD, TAPC, TFB, TPD, and diamine derivative.

55. The IR-to-visible upconversion device according to claim 52, wherein the LEL comprises at least one material selected from the group consisting of Iridium tris(2-phenylpyidine) (Ir(ppy)3), [2-methoxy-5-(2-ethylhexyloxy)-p-phenylenevinylene] (MEH-PPV), Tris-(8-quinolinolato) aluminum) (Alq3), and bis[(4,6-di-fluorophenyl)-pyridinate-]picolinate (Flrpic).

56. The IR-to-visible upconversion device according to claim 52, wherein the ETL comprises at least one material selected from the group consisting of BCP, Bphen, 3TPYMB, and Alq3.

57. The IR-to-visible upconversion device according to claim 52, wherein the OLED electrode comprises a Mg:Ag/Alq3 stack layer, wherein the Mg:Ag layer of the Mg:Ag/Alq3 stack layer has a composition of Mg:Ag (10:1), wherein the Mg:Ag layer has a thickness of less than 30nm, and wherein the Alq3 layer of the Mg:Ag/Alq3 stack layer has a thickness of no more than 200 nm.

58. The IR-to-visible upconversion device according to claim 52,

wherein the electron blocking/tunneling layer is a TAPC/MoO_3 stack layer,

wherein the TAPC layer is in direct contact with the light sensitizing layer,

wherein the MoO_3 layer is in direct contact with the second photodetector electrode, and

wherein the light sensitizing layer comprises PbS quantum dots.

59. The IR-to-visible upconversion device according to claim 58, further comprising a hole blocking layer on the first photodetector electrode and under the light sensitizing layer.

60. The IR-to-visible upconversion device according to claim 52, wherein the photodetector with gain is positioned directly adjacent to the OLED, and wherein the OLED is positioned such that the ETL of the OLED is closer to the light sensitizing layer of the photodetector with gain than it is to the electron blocking/tunneling layer of the photodetector with gain.

61. The IR-to-visible upconversion device according to claim 52, further comprising an interconnecting part between the photodetector with gain and the OLED, wherein the interconnecting part is positioned such that the electron blocking/tunneling layer of the photodetector with gain is closer than the light sensitizing layer is to the interconnecting part, and wherein the interconnecting part is positioned such that the HTL of the OLED is closer than the ETL is to the interconnecting part.

62. The IR-to-visible upconversion device according to claim 61, wherein the interconnecting part comprises a hole blocking layer (HBL) and an electron blocking layer (EBL),

wherein the interconnecting part is positioned such that the HBL of the interconnecting part is adjacent to and in direct contact with the second photodetector electrode, and

wherein the interconnecting part is positioned such that EBL of the interconnecting part is adjacent to and in direct contact with the HTL of the OLED.

63. The IR-to-visible upconversion device according to claim 62, wherein a lowest unoccupied molecular orbital (LUMO) of the HBL of the interconnecting part is within 0.5 electron volts (eV) of a highest occupied molecular orbital (HOMO) of the EBL of the interconnecting part.

64. The IR-to-visible upconversion device according to claim 37, further comprising an interconnecting part between the photodetector with gain and the OLED, wherein the interconnecting part is positioned such that the electron blocking/tunneling layer of the photodetector with gain is closer than the light sensitizing layer is to the interconnecting part.

65. The IR-to-visible upconversion device according to claim 64, wherein the interconnecting part comprises a hole blocking layer (HBL) and an electron blocking layer (EBL),

wherein the interconnecting part is positioned such that the HBL of the interconnecting part is adjacent to and in direct contact with the second photodetector electrode, and

wherein the interconnecting part is positioned such that EBL of the interconnecting part is adjacent to and in direct contact with the HTL of the OLED.

66. The IR-to-visible upconversion device according to claim 65, wherein a lowest unoccupied molecular orbital (LUMO) of the HBL of the interconnecting part is within 0.5 electron volts (eV) of a highest occupied molecular orbital (HOMO) of the EBL of the interconnecting part.

67. A method of forming an IR-to-visible upconversion device, comprising:

forming a photodetector with gain;

forming an OLED; and

coupling the OLED to the photodetector with gain,

wherein forming the photodetector with gain comprises:

forming a first electrode;

forming a light sensitizing layer on the first electrode;

forming an electron blocking/tunneling layer on the light sensitizing layer; and

forming a second electrode on the electron blocking/tunneling layer.

68. The method according to claim 67, wherein the light sensitizing layer is sensitive to photons having a wavelength in a range of from 0.7 μm to 14 μm, inclusive.

69. The method according to claim 68, wherein the light sensitizing layer is insensitive to photons having a wavelength of at least 0.4 μm and less than 0.7 μm.

70. The method according to claim 67, wherein the light sensitizing layer comprises PbS quantum dots or PbSe quantum dots.

71. The method according to claim 67, wherein the light sensitizing layer comprises PbS quantum dots.

72. The method according to claim 67, wherein the light sensitizing layer comprises at least one material selected from the group consisting of PbS quantum dots, PbSe quantum dots, PCTDA, SnPc, SnPc:C60, AlPcCl, AlPcCl:C60, TiOPc, TiOPc:C60, PbSe, PbS, InAs, InGaAs, Si, Ge, and GaAs.

73. The method according to claim 67, wherein the first photodetector electrode comprises at least one material selected from the group consisting of indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

74. The method according to claim 67, wherein the second photodetector electrode comprises at least one material selected from the group consisting of indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

75. The method according to claim 67, wherein the first photodetector electrode is an anode, and wherein the second photodetector electrode is a cathode.

76. The method according to claim 75, wherein the first photodetector electrode comprises at least one material selected from the group consisting of indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO; and wherein the second photodetector electrode comprises at least one material selected from the group consisting of indium tin oxide (ITO), indium zinc oxide (IZO), aluminum tin oxide (ATO), aluminum zinc oxide (AZO), silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, and $CsCO_3$/ITO.

77. The method according to claim 67, wherein forming the electron blocking/tunneling layer comprises forming a TAPC/MoO_3 stack layer.

78. The method according to claim 77, wherein the TAPC layer is formed in direct contact with the light sensitizing layer, and wherein the second photodetector electrode is formed in direct contact with the MoO_3 layer.

79. The method according to claim 77, wherein the TAPC layer has a thickness of no more than 100 nm, and wherein the MoO_3 layer has a thickness of no more than 100 nm.

80. The method according to claim 67, further comprising forming a hole blocking layer on the first photodetector electrode, wherein the light sensitizing layer is formed on the hole blocking layer.

81. The method according to claim 80, wherein the hole blocking layer comprises at least one material selected from the group consisting of ZnO, naphthalene tetracarboxylic anhydride (NTCDA), 2,9-Dimethyl-4,7-diphenyl-1,10-phenanthroline (BCP), p-bis(triphenylsilyl)benzene (UGH2), 4,7-diphenyl-1,10-phenanthroline (BPhen), tris-(8-hydroxy quinoline) aluminum (Alq3), 3,5'-N,N'-dicarbazole-benzene (mCP), C60, tris[3-(3-pyridyl)-mesityl]borane (3TPYMB), and TiO_2.

82. The method according to claim 67, wherein forming the OLED comprises:

forming an OLED electrode;

forming a hole transporting layer (HTL);

forming a light emitting layer (LEL); and

forming an electron transporting layer (ETL).

83. The method according to claim 82, wherein the OLED electrode comprises at least one material selected from the group consisting of ITO, IZO, ATO, AZO, silver, calcium, magnesium, gold, aluminum, carbon nanotubes, silver nanowire, LiF/Al/ITO, Ag/ITO, $CsCO_3$/ITO, and a Mg:Ag/Alq3 stack layer.

84. The method according to claim 82, wherein the HTL comprises at least one material selected from the group consisting of NPD, TAPC, TFB, TPD, and diamine derivative.

85. The method according to claim 82, wherein the LEL comprises at least one material selected from the group consisting of Iridium tris(2-phenylpyidine) (Ir(ppy)3), [2-methoxy-5-(2-ethylhexyloxy)-p-phenylenevinylene] (MEH-PPV), Tris-(8-quinolinolato) aluminum) (Alq3), and bis[(4,6-di-fluorophenyl)-pyridinate-]picolinate (Flrpic).

86. The method according to claim 82, wherein the ETL comprises at least one material selected from the group consisting of BCP, Bphen, 3TPYMB, and Alq3.

87. The method according to claim 82, wherein forming the OLED electrode comprises forming a Mg:Ag/Alq3 stack layer, wherein the Mg:Ag layer of the Mg:Ag/Alq3 stack layer has a composition of Mg:Ag (10:1), wherein the Mg:Ag layer has a thickness of less than 30nm, and wherein the Alq3 layer of the Mg:Ag/Alq3 stack layer has a thickness of no more than 200 nm.

88. The method according to claim 82,

wherein forming the electron blocking/tunneling layer comprises forming a TAPC/MoO_3 stack layer,

wherein the TAPC layer is formed in direct contact with the light sensitizing layer,

wherein the second photodetector electrode is formed in direct contact with the MoO_3 layer, and

wherein the light sensitizing layer comprises PbS quantum dots.

89. The method according to claim 88, further comprising forming a hole blocking layer on the first photodetector electrode, wherein the light sensitizing layer is formed on the hole blocking layer.

90. The method according to claim 82, wherein the photodetector with gain is positioned directly adjacent to the OLED, and wherein the OLED is positioned such that the ETL of the OLED is closer to the light sensitizing layer of the photodetector with gain than it is to the electron blocking/tunneling layer of the photodetector with gain.

91. The method according to claim 78, wherein coupling the OLED to the photodetector with gain comprises:

forming an interconnecting part;

coupling the OLED to the interconnecting part; and

coupling the photodetector with gain to the interconnecting part,

wherein the interconnecting part is positioned such that the electron blocking/tunneling layer of the photodetector with gain is closer than the light sensitizing layer is to the interconnecting part, and

wherein the interconnecting part is positioned such that the HTL of the OLED is closer than the ETL is to the interconnecting part.

92. The method according to claim 91, wherein forming the interconnecting part comprises:

forming a hole blocking layer (HBL); and

forming electron blocking layer (EBL),

wherein the interconnecting part is positioned such that the HBL of the interconnecting part is adjacent to and in direct contact with the second photodetector electrode, and

wherein the interconnecting part is positioned such that EBL of the interconnecting part is adjacent to and in direct contact with the HTL of the OLED.

93. The method according to claim 92, wherein a lowest unoccupied molecular orbital (LUMO) of the HBL of the interconnecting part is within 0.5 electron volts (eV) of a highest occupied molecular orbital (HOMO) of the EBL of the interconnecting part.

94. The method according to claim 63, wherein coupling the OLED to the photodetector with gain comprises:

forming an interconnecting part;

coupling the OLED to the interconnecting part; and

coupling the photodetector with gain to the interconnecting part,

wherein the interconnecting part is positioned such that the electron blocking/tunneling layer of the photodetector with gain is closer than the light sensitizing layer is to the interconnecting part.

95. The method according to claim 94, wherein forming the interconnecting part comprises:

forming a hole blocking layer (HBL); and

forming electron blocking layer (EBL),

wherein the interconnecting part is positioned such that the HBL of the interconnecting part is adjacent to and in direct contact with the second photodetector electrode, and

wherein the interconnecting part is positioned such that EBL of the interconnecting part is adjacent to and in direct contact with the HTL of the OLED.

96. The method according to claim 95, wherein a lowest unoccupied molecular orbital (LUMO) of the HBL of the interconnecting part is within 0.5 electron volts (eV) of a highest occupied molecular orbital (HOMO) of the EBL of the interconnecting part.

97. A method of detecting IR radiation using a photodetector with gain, comprising:

providing a photodetector with gain, such that IR radiation is incident upon the photodetector with gain,

wherein the photodetector with gain comprises:

a first electrode;

an IR light sensitizing layer on the first electrode;

an electron blocking/tunneling layer on the light sensitizing layer; and

a second electrode on the electron blocking/tunneling layer.

98. A method of upconverting IR radiation to visible radiation using an IR-to-visible upconversion device, comprising:

providing an IR-to-visible upconversion device such that IR radiation is incident upon the IR-to-visible upconversion device,

wherein the IR-to-visible upconversion device comprises:

a photodetector with gain; and

an organic light-emitting device (OLED) coupled to the photodetector with gain,

wherein the photodetector with gain comprises:

a first photodetector electrode;

an IR light sensitizing layer on the first photodetector electrode;

an electron blocking/tunneling layer on the light sensitizing layer; and

a second photodetector electrode on the electron blocking/tunneling layer.