PHOTODETECTOR AND METHOD OF FORMING THE SAME

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority of Singapore application No. 10202250451P filed July 13, 2022, the contents of it being hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] Various embodiments of this disclosure may relate to a photodetector. Various embodiments of this disclosure may relate to a method of forming a photodetector.

BACKGROUND

[0003] Polarimetry of light is crucial in modern navigation, missile guidance, military reconnaissance and remote sensing, especially in the infrared range (IR) that is invisible and permeable for naked eyes. Conventional polarization discrimination mainly relies on a hybrid system that includes bulky polarized optical components and photodetector units or arrays. For classification, four types of technical routines are typically employed in commercial polarimetric imaging systems, including time-, amplitude-, local area- and focal plane-resolved methods, respectively. Although these listed strategies are widely employed for a range of applications, disadvantages such as complex structures, high cost and processing difficulty would still need to be resolved.

[0004] Recently, upon the advances of newly emerged structure configuration, mechanism and materials, several downscaled polarization-sensitive photodetectors have been explored for realization of on-chip ultra-miniaturized polarimeters. Specifically, artificial micro/nano-photonic structures utilizing such as surface plasmons and metasurfaces, with arbitrary building

blocks can generate optical anisotropy, thereby enabling detectors with the ability for polarization detection. With careful design and geometric arrangement, some of them are able to achieve measurement of the linear state of polarization (SOP). However, the artificial nanostructures are functionalized as optical filters, which not only limit the downscaling of device size, but also increase the manufacturing complexity due to the sensitivity of the optical properties on the antenna dimensions. Moreover, unnecessary energy loss from the photonic nanostructures may also affect the performance of integrated detectors.

SUMMARY

[0005] Various embodiments may provide a photodetector. The photodetector may include a first layer of a first material having a first crystal orientation. The photodetector may also include a second layer of the first material having a second crystal orientation different from the first material of the first layer. The photodetector may further include a third (middle) layer of a second material between the first layer and the second layer. A bandgap of the second material may be larger than a bandgap of the first material. The first crystal orientation and the second crystal orientation may be non-perpendicular and non-parallel to each other. The photodetector may, under an initial (or first) voltage bias between the first layer and the second layer, be configured to generate a first photocurrent upon incidence of a first polarized light having a first polarization angle onto the photodetector. The photodetector may also, under the initial (or first) voltage bias between the first layer and the second layer, be configured to generate a second photocurrent of a magnitude different from a magnitude of the first photocurrent upon incidence of a second polarized light having a second polarization angle different to the first polarization angle onto the photodetector.

[0006] Various embodiments may provide a method of forming a photodetector. The method may include forming a first layer of a first material having a first crystal orientation.

The method may also include forming a second layer of the first material having a second crystal orientation different from the first material of the first layer. The method may further include forming a third (middle) layer of a second material between the first layer and the second layer. A bandgap of the second material may be larger than a bandgap of the first material. A bandgap of the second material may be larger than a bandgap of the first material. The first crystal orientation and the second crystal orientation may be non-perpendicular and non-parallel to each other. The photodetector, under an initial (or first) voltage bias between the first layer and the second layer, may be configured to generate a first photocurrent upon incidence of a first polarized light having a first polarization angle onto the photodetector. The photodetector, under the initial (or first) voltage bias between the first layer and the second layer, may be configured to generate a second photocurrent of a magnitude different from a magnitude of the first photocurrent upon incidence of a second polarized light having a second polarization angle different to the first polarization angle onto the photodetector.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily drawn to scale, emphasis instead generally being placed upon illustrating the principles of various embodiments. In the following description, various embodiments of the invention are described with reference to the following drawings.

FIG. 1 shows a schematic of a photodetector according to various embodiments.

FIG. 2 shows a schematic of a method of forming a photodetector according to various embodiments.

FIG. 3A is a schematic of perspective view of a linear polarization-sensitive photodetector according to various embodiments, with the inset showing a side view of the photodetector according to various embodiments.

FIG. 3B shows (above) a polarized Raman spectrum and (bottom) an absorption spectrum of black arsenic phosphorous (b-AsP) according to various embodiments.

FIG. 3C shows a line drawing of the fabricated twisted unipolar barrier black arsenic phosphorous/ tungsten disulfide/ black arsenic phosphorous (b-AsP/WS_2/b-AsP) photodetector according to various embodiments.

FIG. 3D shows plots of angle (in degree or º) as a function of wavenumber (per centimeter or cm^{-1}) illustrating the polarized Raman spectra of the top black arsenic phosphorous (b-AsP) layer and bottom black arsenic phosphorous (b-AsP) layer according to various embodiments.

FIG. 4A shows a plot of energy (in electron-Volts or eV) as a function of position (in nanometers or nm) illustrating the simulated energy band structure of the photodetector at V_{ds} = 0V according to various embodiments.

FIG. 4B shows a plot of energy (in electron-Volts or eV) as a function of position (in nanometers or nm) illustrating the simulated energy band structure of the photodetector at V_{ds} = -0.1V according to various embodiments.

FIG. 4C shows a plot of energy (in electron-Volts or eV) as a function of position (in nanometers or nm) illustrating the simulated energy band structure of the photodetector at V_{ds} = 0.1V according to various embodiments.

FIG. 4D is a plot of drain current (in nano-amperes or nA) as a function of bias voltage V_{ds} (in volts or V) illustrating output curves as a function of incident power at illumination wavelength of 4.6 μm according to various embodiments.

FIG. 4E shows a plot of photocurrent (in nano-Amperes or nA) as a function of power (in micro-Watts or μW) illustrating the dependence of photocurrents on the incident power at V_{ds} = -0.1

V and V_{ds} = 0.1 V with angle of linear polarization (AoLP) of 0° and 110° according to various embodiments.

FIG. 4F shows a plot of normalized photoresponse as a function of time (in milliseconds or ms) illustrating a fast response speed of the device according to various embodiments, of which the rise time and fall time are ~200 μs. From the result, a fast photoresponse speed of ~200 μs was achieved in the device.

FIG. 5A is a plot of photocurrent (in nano-Amperes or nA) as a function of time (in seconds or s) illustrating the time dependence of photocurrents of the photodetector at -0.1V with the incident angle of linear polarization (AoLP) sweeping from 0º to 360º according to various embodiments.

FIG. 5B is a plot of photocurrent (in nano-Amperes or nA) as a function of time (in seconds or s) illustrating the time dependence of photocurrents of the photodetector at 0.1V with the incident angle of linear polarization (AoLP) sweeping from 0º to 360º according to various embodiments.

FIG. 5C shows polar plots of the forward bias 0.1V driven photocurrents and reverse bias -0.1V driven photocurrents excited by different incident angles of linear polarization (AoLP) from 0 to 360° according to various embodiments.

FIG. 5D is a plot of reverse bias I_{ph} (in nano-Amperes or nA) as a function of forward bias I_{ph} (in nano-Amperes or nA) illustrating two-dimensional (2D) plots of forward bias I_{ph1} and reverse bias I_{ph2} in cartesian coordinate system where the photocurrent pair (I_{ph1}, I_{ph2}) can be well fitted by a closed ellipse equation when the angles of linear polarization (AoLP) change from 0 to 180° according to various embodiments, of which the relationship enable the reconstruction of any unknown incident linear state of polarization (SOP).

FIG. 6A is a schematic of a home-built single-pixel scanning system according to various embodiments.

FIG. 6B shows the light intensity images of the target at forward bias and reverse bias by the device according to various embodiments.

FIG. 6C shows the computational reconstructed polarimetric image of the object described by the angles of polarization (AoP) according to various embodiments, from which more information of the target is obtained. Specifically, the angles of linear polarization (AoLP) of "1" around 170° and 70°of "2" are identical with the present conditions.

FIG. 7A shows an optical image of exfoliated black arsenic phosphorous (b-AsP) sample on a calcium difluoride (CaF_2) substrate according to various embodiments. The scale bar represents 30 μm.

FIG. 7B is a plot of height (in nanometer) as a function of position (in micrometer) showing the height profile black arsenic phosphorous (b-AsP) sample on the calcium difluoride (CaF_2) substrate, with the inset showing the atomic force microscopy image of the sample according to various embodiments.

FIG. 7C shows a plot of intensity (in arbitrary units or a.u.) as a function of wavenumber (in per centimeter or cm^{-1}) illustrating the Raman spectra of the sample according to various embodiments.

FIG. 7D shows the intensity ratio of $I(A_g^1)/I(A_g^2)$ dependent on the different angles according to various embodiments.

FIG. 8A is a plot of transmission as a function of wavenumber (per centimeter or cm^{-1}) illustrating the polarized transmission of the black arsenic phosphorous (b-AsP) in the range of 1500 cm^{-1} to 4000 cm^{-1} according to various embodiments.

FIG. 8B is a plot of reflection as a function of wavenumber (per centimeter or cm^{-1}) illustrating the polarized reflection of the black arsenic phosphorous (b-AsP) in the range of 1500 cm^{-1} to 4000 cm^{-1} according to various embodiments.

FIG. 8C is a plot of absorption as a function of wavenumber (per centimeter or cm^{-1}) illustrating the polarized absorption of the black arsenic phosphorous (b-AsP) in the range of 1500 cm^{-1} to 4000 cm^{-1} according to various embodiments.

FIG. 9A shows a plot of current (in nano-Amperes or nA) as a function of drain-source voltage V_{ds} (in volts or V) illustrating the output curve of a tungsten disulfide (WS_2) field effect transistor (FET) according to various embodiments.

FIG. 9B shows a plot of current (in nano-Amperes or nA) as a function of drain-source voltage V_{ds} (in volts or V) illustrating the output curve of a black arsenic phosphorous (b-AsP) field effect transistor (FET) according to various embodiments.

FIG. 9C shows a plot of current (in nano-Amperes or nA) as a function of gate voltage V_g (in volts or V) illustrating the transfer curve of the tungsten disulfide (WS_2) field effect transistor (FET) according to various embodiments.

FIG. 9D shows a plot of current (in nano-Amperes or nA) as a function of gate voltage V_g (in volts or V) illustrating the transfer curve of the black arsenic phosphorous (b-AsP) field effect transistor (FET) according to various embodiments.

FIG. 10A shows an atomic force microscopy (AFM) surface topography image of heterostructure photodetector according to various embodiments. The scale bar represents 5 μm.

FIG. 10B shows a plot of height (in nanometers) as a function of position (in micrometers or μm) illustrating the height profile of the middle tungsten disulfide (WS_2) layer according to various embodiments.

FIG. 10C shows a plot of height (in nanometers) as a function of position (in micrometers or μm) illustrating the height profile of the bottom black arsenic phosphorous (b-AsP) layer according to various embodiments.

FIG. 10D shows a plot of height (in nanometers) as a function of position (in micrometers or μm) illustrating the height profile of the top black arsenic phosphorous (b-AsP) layer according to various embodiments.

FIG. 11A shows a plot of photovoltage V_{ph} (in milli-Volts or mV) as a function of power (in micro-Watts or μW) illustrating the dependence of photovoltage on incident power of light with polarization states of 0º and 110º according to various embodiments.

FIG. 11B shows a plot of photocurrent I_{ph} (in nano-Amperes or nA) as a function of photovoltage V_{ph} (in milli-Volts or mV) illustrating the relationship between short circuit current and open circuit voltage due to incidence of light at 0º according to various embodiments.

FIG. 11C shows a plot of photocurrent I_{ph} (in nano-Amperes or nA) as a function of photovoltage V_{ph} (in milli-Volts or mV) illustrating the relationship between short circuit current and open circuit voltage due to incidence of light at 110º according to various embodiments.

FIG. 11D is a plot of responsivity (in volts per Watt or V/W) as a function of power (in micro-Watts or μW) illustrating the dependence of responsivity on the incident power at 0 V at state of polarization (SOP) of 0º and 110º according to various embodiments.

FIG. 11E shows a plot of noise (in nano-Volts per Hertz square-root or nV $Hz^{-0.5}$) as a function of frequency (in Hertz or Hz) illustrating the measured frequency dependence on noise according to various embodiments.

FIG. 11F shows a plot of noise equivalent power NEP (in Watts Hertz square-root or W $Hz^{0.5}$) / specific detectivity D* (in centimeter Hertz square-root per Watt or cm $Hz^{0.5}$ W^{-1}) as a function of power (in micro-Watts or μW) illustrating the dependence of NEP and D* at states of polarization of 0º and 110º according to various embodiments.

FIG. 12A shows a plot of photocurrent (in nano-Amperes or nA) as a function of angle (in degrees or º) illustrating the bipolarity dependence on the state of polarization (SOP) at bias voltage of 0V according to various embodiments.

FIG. 12B shows a plot of drain current (in nano-Amperes or nA) as a function of time (in seconds or s) illustrating the time-dependence of the photoresponse according to various embodiments.

FIG. 13A shows a plot of photoresponse (in arbitrary units or a.u.) as a function of state of polarization (SOP) angle (in degrees or º) illustrating the theoretical polarized photoresponse at different bias depending on the bottom layer and the top layer according to various embodiments.

FIG. 13B shows a plot of photoresponse (in arbitrary units or a.u.) as a function of state of polarization (SOP) angle (in degrees or º) illustrating the theoretical polarized photoresponse at different angles between the bottom layer and the top layer according to various embodiments.

FIG. 13C is a plot of the top photoresponse (in arbitrary units or a.u.) as a function of the bottom photoresponse (in arbitrary units or a.u.) illustrating the photoresponse with bottom black arsenic phosphorous (b-AsP) layer as absorber at forward bias and top black arsenic phosphorous (b-AsP) layer as absorber at reverse bias, respectively according to various embodiments.

FIG. 14A shows polar plots of the forward bias 1V driven photocurrents and reverse bias -0.5V driven photocurrents excited by different incident angles of linear polarization (AoLP) from 0 to 360° according to various embodiments.

FIG. 14B is a plot of reverse bias photocurrent I_{ph} (in nano-Amperes or nA) as a function of forward bias photocurrent I_{ph} (in nano-Amperes or nA) illustrating two-dimensional (2D) plots of forward bias photocurrent I_{ph1} and reverse bias photocurrent I_{ph2} in cartesian coordinate system where the photocurrent pair (I_{ph1}, I_{ph2}) can be well fitted by a closed ellipse equation

when the angles of linear polarization (AoLP) change from 0 to 180° according to various embodiments when the photodetector is at -0.5V and 1V bias voltage and illuminated with a 4.6 μm laser.

FIG. 14C is a plot of photocurrent (in nano-Amperes or nA) as a function of time (in seconds or s) illustrating the time dependence of photocurrents of the photodetector at -0.5V with the incident angle of linear polarization (AoLP) sweeping from 0º to 360º according to various embodiments.

FIG. 14D is a plot of photocurrent (in nano-Amperes or nA) as a function of time (in seconds or s) illustrating the time dependence of photocurrents of the photodetector at 1V with the incident angle of linear polarization (AoLP) sweeping from 0º to 360º according to various embodiments.

DESCRIPTION

[0008] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0009] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or

combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0010] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0011] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance, e.g. within 10% of the specified value.

[0012] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0013] By “comprising” it is meant including, but not limited to, whatever follows the word “comprising”. Thus, use of the term “comprising” indicates that the listed elements are required or mandatory, but that other elements are optional and may or may not be present.

[0014] By “consisting of” is meant including, and limited to, whatever follows the phrase “consisting of”. Thus, the phrase “consisting of” indicates that the listed elements are required or mandatory, and that no other elements may be present.

[0015] Embodiments described in the context of one of the photodetectors are analogously valid for the other photodetectors. Similarly, embodiments described in the context of a method are analogously valid for a photodetector, and vice versa.

[0016] Given the above limitations, two-dimensional (2D) materials-based polarization-sensitive photodetectors are booming due to their superior optical property of natural anisotropy that stems from the intrinsic crystal asymmetries. These intrinsically-emerged anisotropic features in 2D materials, such as germanium selenide (GeSe), rhenium disulfide (ReS_2), rhenium diselenide ($ReSe_2$), black phosphorus (BP), black arsenic phosphorus (b-AsP), tellurium, lead diselenide ($PdSe_2$), molybdenum disulfide (MoS_2) and their related van der Waals heterostructures (vdWHs) enable broadband polarization photodetection under filter-free

operation, which is promising for ultra-compact polarimetry of highly integrated optoelectronics. However, the filter-free full linear polarimetry by single device is still hard to realize because the photocurrent signals overlap twice when the linear SOP of light changes by a period.

[0017] FIG. 1 shows a schematic of a photodetector according to various embodiments. The photodetector may include a first layer 102 of a first material having a first crystal orientation. The photodetector may also include a second layer 104 of the first material having a second crystal orientation different from the first material of the first layer 102. The photodetector may further include a third (middle) layer 106 of a second material between the first layer 102 and the second layer 104. A bandgap of the second material may be larger than a bandgap of the first material. The first crystal orientation and the second crystal orientation may be non-perpendicular and non-parallel to each other. The photodetector may, under an initial (or first) voltage bias between the first layer 102 and the second layer 104, be configured to generate a first photocurrent upon incidence of a first polarized light having a first polarization angle onto the photodetector. The photodetector may also, under the initial (or first) voltage bias between the first layer 102 and the second layer 104, be configured to generate a second photocurrent of a magnitude different from a magnitude of the first photocurrent upon incidence of a second polarized light having a second polarization angle different to the first polarization angle onto the photodetector.

[0018] In other words, the photodetector may include two layers 102, 104 of a first material and a middle third layer 106 of a second material between the two layers 102, 104. The first layer 102 may have a crystal orientation different from, and non-perpendicular and non-parallel to, a crystal orientation of the second layer 104. The bandgap of the second material may be larger than a bandgap of the first material such that the photodetector, under an applied voltage,

may generate different photocurrents when different polarized lights have different polarization angles are incident on the photodetector.

[0019] For avoidance of doubt, FIG. 1 serves to illustrate some features according to various embodiments, and is not intended to limit, for instance, the dimensions, shape, orientation etc. of the various components.

[0020] In various embodiments, there may be nearly no or a very small barrier for electrons and a high barrier for holes, which may be achieved by energy band alignment. The holes traveling from the first layer 102 or the second layer 104 may face the high barrier when passing into the third (middle) layer. In other words, the photodetector may be configured such that an energy barrier for holes is higher than an energy barrier for electrons. For instance, the energy barrier for holes may be more than 0.5 eV, e.g. 1.0 eV or 1.2 eV etc.

[0021] In various other embodiments, there may be nearly no or a very small barrier for holes and a high barrier for electrons, which may be achieved by energy band alignment. The electrons traveling from the first layer 102 or the second layer 104 may face the high barrier when passing into the third (middle) layer. In other words, the photodetector may be configured such that an energy barrier for electrons may be higher than an energy barrier for holes. For instance, the energy barrier for electrons may be more than 0.5 eV, e.g. 1.0 eV or 1.2 eV etc.

[0022] In various embodiments, the first layer 102 and the second layer 104 may act as absorbers, while the third layer 106 may act as a barrier.

[0023] In various embodiments, a difference between the first polarization angle and the second polarization angle may be between 0 degree and 180 degrees (not inclusive of 0 degree and 180 degrees).

[0024] In various embodiments, the photodetector, under a subsequent (or second) voltage bias between the first layer 102 and the second layer 104, the subsequent (or second) voltage bias having a polarity different from a polarity of the initial (or first) voltage bias, may be

configured to generate third photocurrent of a magnitude different from a magnitude of the first photocurrent upon incidence of the first polarized light onto the photodetector. In other words, the photodetector, under application of a subsequent (or second) voltage bias of opposite polarity but the same first polarized light may generate a third photocurrent different from the first photocurrent.

[0025] In various embodiments, a photocurrent pair including a forward bias current (under a predetermined forward biasing voltage) and a reverse bias current (under a predetermined reverse biasing voltage) may correspond to a fixed linear state of polarization. In other words, a pair of forward bias current and reverse bias current under a given forward biasing voltage and reverse biasing voltage respectively may correspond to only a single state of polarization of the polarized light. The photocurrent pair under the given forward biasing voltage and reverse biasing voltage may not recur when the angle of polarization of the incident polarized light changes.

[0026] Generally speaking, the first material and the second material may be any suitable material pair such that a bandgap of the second material is larger than a bandgap of the first material. In various embodiments, the first material may be black arsenic phosphorous (b-AsP) and the second material may be tungsten disulfide (WS_2). In various other embodiments, the first material may be black arsenic phosphorous (b-AsP) and the second material may be molybdenum disulfide (MoS_2). In yet various other embodiments, the first material may be germanium selenide (GeSe) and the second material may be gallium selenide (GaSe). In yet various other embodiments, the first material may be GeSe and the second material may be tin sulfide (SnS_2).

[0027] In various embodiments, the photodetector may have a van der Waals heterostructure (vdWH). The photodetector may be referred to as a van der Waals heterostructure (vdW) photodetector or device, or more simply as a heterostructure. In various embodiments, the first

layer 102, the second layer 104 and the middle third layer 106 may be 2-dimensional (2D) layers (i.e. monolayers). There may be van der Waals forces between the first layer 102 and the third layer 106. Likewise, there may be van der Waals forces between the second layer 104 and the third layer 106. In contrast, atoms within each layer may be held by covalent bonds.

[0028] In various embodiments, the photodetector may include a first electrode electrically connected to the first layer. The photodetector may include a second electrode electrically connected to the second layer. The first electrode may include any suitable electrically conductive material, e.g. a metal such as gold (Au), chromium (Cr) or platinum (Pt). The second electrode may include any suitable electrically conductive material, e.g. a metal such as gold (Au), chromium (Cr) or platinum (Pt). Alternatively, the first electrode and/or the second electrode may include an electrically conductive material such as graphene.

[0029] FIG. 2 shows a schematic of a method of forming a photodetector according to various embodiments. The method may include, in 202, forming a first layer of a first material having a first crystal orientation. The method may also include, in 204, forming a second layer of the first material having a second crystal orientation different from the first material of the first layer. The method may further include, in 206, forming a third (middle) layer of a second material between the first layer and the second layer. A bandgap of the second material may be larger than a bandgap of the first material. The first crystal orientation and the second crystal orientation may be non-perpendicular and non-parallel to each other. The photodetector, under an initial (or first) voltage bias between the first layer and the second layer, may be configured to generate a first photocurrent upon incidence of a first polarized light having a first polarization angle onto the photodetector. The photodetector, under the initial (or first) voltage bias between the first layer and the second layer, may be configured to generate a second photocurrent of a magnitude different from a magnitude of the first photocurrent upon incidence

of a second polarized light having a second polarization angle different to the first polarization angle onto the photodetector.

[0030] In other words, the method may include forming the first layer, the second layer and the third (middle) layer such that the first crystal orientation and the second crystal orientation are non-perpendicular and non-parallel to each other, and a bandgap of the second material is larger than a bandgap of the first material.

[0031] For avoidance of doubt, FIG. 2 is not intended to limit the sequence of the various steps. For instance, step 202 may occur before, after or at the same time as step 204.

[0032] In various embodiments, step 202 may occur first, followed by step 206 and finally step 204. The middle third layer may be on or over the first layer (bottom layer), and the second layer (top layer) may be on or over the middle third layer. In various other embodiments, step 204 may occur first, followed by step 206 and finally step 202. The middle third layer may be on or over the second layer (bottom layer), and the first layer (top layer) may be on or over the middle third layer. In other words, the first layer, the second layer and the third layer may form a three-layers stacked arrangement, and the layer that is at the bottom of the stacked arrangement may be referred to as the bottom layer, while the layer that is at the top of the stacked arrangement may be referred to as the top layer.

[0033] In various embodiments, the first layer, the second layer and/or the third layer may be formed by mechanical exfoliation. The bottom layer may be provided onto a substrate using dry transfer. The middle layer may be provided onto the bottom layer via dry transfer. The top layer may be provided onto the middle layer via dry transfer. Dry transfer may be carried out using a suitable transfer medium such as a polydimethylsiloxane (PDMS) stamp. The first layer, the second layer and/or the third layer may be exfoliated on the transfer medium prior to dry transfer.

[0034] In various embodiments, there may be a small barrier for electrons and a high barrier for holes, which may be achieved by energy band alignment. In other words, the photodetector may be configured such that an energy barrier for holes is higher than an energy barrier for electrons. For instance, the energy barrier for holes may be more than 1.0 eV, e.g. more than 1.2 eV.

[0035] In various other embodiments, there may be a small barrier for holes and a high barrier for electrons, which may be achieved by energy band alignment. In other words, the photodetector may be configured such that an energy barrier for electrons may be higher than an energy barrier for holes. For instance, the energy barrier for electrons may be more than 1.0 eV, e.g. more than 1.2 eV.

[0036] In various embodiments, a difference between the first polarization angle and the second polarization angle may be between 0 degree and 180 degrees (not inclusive of 0 degree and 180 degrees).

[0037] In various embodiments, the photodetector, under a subsequent (or second) voltage bias between the first layer and the second layer, the subsequent voltage bias having a polarity different from a polarity of the initial (or second) voltage bias, may be configured to generate third photocurrent of a magnitude different from a magnitude of the first photocurrent upon incidence of the first polarized light onto the photodetector. In other words, the photodetector, under application of a subsequent (or second) voltage bias of opposite polarity but the same first polarized light may generate a third photocurrent different from the first photocurrent.

[0038] In various embodiments, a photocurrent pair including a forward bias current under a predetermined forward biasing voltage and a reverse bias current under a predetermined reverse biasing voltage may correspond to a fixed linear state of polarization.

[0039] Generally speaking, the first material and the second material may be any suitable material pair such that a bandgap of the second material is larger than a bandgap of the first

material. In various embodiments, the first material may be black arsenic phosphorous (b-AsP) and the second material may be tungsten disulfide (WS_2). In various other embodiments, the first material may be black arsenic phosphorous (b-AsP) and the second material may be molybdenum disulfide (MoS_2). In yet various other embodiments, the first material may be germanium selenide (GeSe) and the second material may be gallium selenide (GaSe). In yet various other embodiments, the first material may be GeSe and the second material may be tin sulfide (SnS_2).

[0040] In various embodiments, the photodetector may have a van der Waals heterostructure.

[0041] In various embodiments, the photodetector may include a first electrode electrically connected to the first layer. The photodetector may include a second electrode electrically connected to the second layer. The method may include forming the first electrode electrically connected to the first layer, e.g. using electron-beam lithography, thermal evaporation disposition and standard lift-off process. The method may include forming the second electrode electrically connected to the second layer, e.g. using electron-beam lithography, thermal evaporation disposition and standard lift-off process.

[0042] Various embodiments may relate to a twisted unipolar barrier based on two dimensional-van der Waals heterostructure (2D-vdWH) constructed by black arsenic phosphorous/ tungsten disulfide/ black arsenic phosphorous (b-AsP/WS_2/b-AsP) to realize polarization-sensitive photodetector that can functionalize for linear polarimetry in the MIR range without using additional plasmonic/metasurface nanostructure. The existence of unipolar barrier with carefully constructed band structure, e.g., small barrier for electrons and high barrier for holes, may enable the bias-switchable photocurrent that is dominated by the natural anisotropic absorption at the top layer (e.g. the second layer) and the bottom layer (e.g. the first layer), respectively, to be the corresponding electrodes. Therefore, by employing one single

detector that is modulated by the switchable bias, two different photo-excited electrical signals may be collected at a given polarization orientation angle. As a result, accurate mid infrared (MIR) linear polarimetry, i.e., any unknown linear state of polarization (SOP), can be calculated by a computational reconstruction algorithm without any rotation of detection samples. Notably, the proposed mechanism may be applicable to a wide range of wavelengths. Mid-IR may be used as a demonstration herein. Finally, scanning polarimetric imaging is demonstrated, which may further indicate the great application potential for such polarization photodetector in the future on-chip polarimeter.

[0043] FIG. 3A is a schematic of perspective view of a linear polarization-sensitive photodetector according to various embodiments, with the inset showing a side view of the photodetector according to various embodiments. The photodetector may have an unipolar barrier including a vertically stacked b-AsP/WS_2/b-AsP vdWH, where b-AsP and WS_2 serve as the MIR absorbers and barrier layer for major carriers, respectively. The bottom b-AsP layer may be grounded. The b-AsP features narrow bandgap, anisotropic optical absorption and high hole mobility, which is prone to achieve the MIR polarization photoresponse. Besides, the WS_2 layer is applied to construct a unipolar barrier owing to its suitable conduction band, which is very close to that of b-AsP layer.

[0044] The b-AsP/WS_2/b-AsP vdWH may be constructed with setting aligning angle of the b-AsP layer to achieve bias-selectable MIR polarization photoresponse. It means that counterpart b-AsP predominates the photoresponse at the corresponding biases due to the orientation difference.

[0045] FIG. 3B shows (above) a polarized Raman spectrum and (bottom) an absorption spectrum of black arsenic phosphorous (b-AsP) according to various embodiments. The maximum polarized absorption at 4.6 μm is along with the armchair (AC) direction. As is shown in FIG. 3B, different intensity ratios $I(A_g^1)/I(A_g^2)$ in the polarized Raman spectra of b-AsP

material strongly demonstrate the anisotropic crystal structure (see more details under "Optical Properties of the b-AsP Absorber" below). A_g^1 and A_g^2 are Raman peaks in the polarized Raman spectra.

[0046] Moreover, the maximum polarized absorption appears when the incident polarization angle is along with the armchair (AC) direction of b-AsP. The polarization-resolved absorption could be well fitted by a $\cos^2(\theta)$ related function. FIG. 3C shows a line drawing of the fabricated twisted unipolar barrier black arsenic phosphorous/ tungsten disulfide/ black arsenic phosphorous (b-AsP/WS_2/b-AsP) photodetector according to various embodiments. The photodetector is marked as D1. The outlines of the bottom b-AsP layer, the top b-AsP layer, and the WS_2 layer are indicated by the dotted lines. The arrows indicate the crystal orientation of the bottom b-AsP layer. The active area is 32 μm^2, and the scale bar indicates 10 μm. The crystal orientations between the top b-AsP layer and bottom AsP layer is ~110°. This is verified by the polarized Raman spectra as shown in FIG. 3D. FIG. 3D shows plots of angle (in degree or º) as a function of wavenumber (per centimeter or cm^{-1}) illustrating the polarized Raman spectra of the top black arsenic phosphorous (b-AsP) layer and bottom black arsenic phosphorous (b-AsP) layer according to various embodiments. The Raman peaks appear for both black arsenic phosphorous (b-AsP) layers and the rotation angle difference between the two layers is about 110º (or 70º). The location marked by the dotted line is the zigzag direction.

[0047] Next, the bias-switchable mid-infrared (MIR) photoresponse mechanism is thoroughly investigated. A theoretical study on the energy band of the unipolar barrier vdWH is processed by a technology computer aided design (TCAD) tool. The selection of model parameters is based on comprehensive consideration of actual sample (see below under "Construction Of Energy Band" for details). FIG. 4A shows a plot of energy (in electron-Volts or eV) as a function of position (in nanometers or nm) illustrating the simulated energy band structure of the photodetector at V_{ds} = 0V according to various embodiments. V_{ds} refers to the

voltage bias between the top layer and the bottom layer. The inset shows the zoom-in of the energy band near the interfaces. FIG. 4B shows a plot of energy (in electron-Volts or eV) as a function of position (in nanometers or nm) illustrating the simulated energy band structure of the photodetector at V_{ds} = -0.1V according to various embodiments. FIG. 4C shows a plot of energy (in electron-Volts or eV) as a function of position (in nanometers or nm) illustrating the simulated energy band structure of the photodetector at V_{ds} = 0.1V according to various embodiments. FIGS. 4B - C also illustrate transport of photoexcited carriers.

[0048] As shown in Fig. 4A, two back-to-back P-N junctions form at a balanced state (V_{ds} = 0 V) and a majority carrier-blocking barrier is established. Here, the junction between bottom b-AsP and WS_2 may be defined as Junction 1 (J1), while the junction between top b-AsP and WS_2 may be defined as J2. When the device is driven by forward bias of 0.1 V, J1 is on the reverse bias while J2 is on the forward bias (FIG. 4C). That means J1 will occupy a predominant role compared to J2 in the photo-excited electron-hole separation process. Similarly, J2 dominates at reverse bias of -0.1 V (FIG. 4B).

[0049] Notably, when the device is illuminated and driven by forward bias (FIG. 4C), photo-excited electrons and holes in the bottom b-AsP layer can be easily separated and may then drift to the electrodes. In this case, the photo-excited holes in the top b-AsP layer are blocked by the barrier, causing the blocked holes to recombine with the photo-excited electrons in top b-AsP layer. Hence, the bottom b-AsP layer nay act as an absorber contributing predominant photocurrent at forward bias.

[0050] On the contrary, so is that at reverse bias (FIG. 4B). Photo-excited electrons and holes in the top b-AsP layer can be easily separated and then drift to the electrodes, while photo-excited holes in the bottom b-AsP layer are blocked by the barrier, causing the blocked holes to recombine with the photo-excited electrons in top b-AsP layer. The top b-AsP layer may act as an absorber contributing predominant photocurrent at reverse bias.

[0051] The switchable photoresponse in the device is also experimentally demonstrated. FIG. 4D is a plot of drain current (in nano-amperes or nA) as a function of bias voltage V_{ds} (in volts or V) illustrating output curves as a function of incident power at illumination wavelength of 4.6 μm according to various embodiments. The initial angle of linear polarization (AoLP) of the incident light is aligned to the AC direction of both bottom b-AsP layer or top b-AsP layer, respectively, which enable the maximum polarized photocurrents at both forward and reverse bias. For convenience and consistency, the angle between AC direction of top b-AsP and the incident AoLP is defined as 0°. When the incident AoLP of light is 0°, significant photoresponse is observed at reverse bias. When the incident AoLP of light is 110°, significant photoresponse is observed at forward bias. The arrow represents increased incident power from 2.85 to 281.54 μW.

[0052] According to the AC direction of top AsP (0°) and bottom b-AsP (110°), the MIR lights with two polarization angles (0° and 110°) are used to illuminate the device. The drain current in dark condition shows an asymmetry feature, which is derived from the unperfect symmetry between J1 and J2. Under illumination, the photoresponse at 0° mainly appears at zero bias and reverse bias while the photoresponse at 110° mainly appears at zero bias and forward bias. Specially, the photoresponse depending on bias and incident linear SOP could be divided into three regions as shown in FIG. 4D.

[0053] Region (i) $-0.063 < V_{ds} < 0.048$ V

[0054] At this region, both J1 and J2 participate in the photoresponse. From the energy band analysis, the reverse bias would enhance J2 and weaken J1, giving the increased photocurrents when the polarization angle of incident light is 0° and decreased photocurrents whilst polarization angle of incident light is 110° if the bias voltage changes from 0.048 to -0.063 V. Otherwise, forward bias would hold the contrary consequence, which leads the increased photocurrents when polarization angle of incident light is 110° and decreased photocurrents

when polarization angle of incident light is 0° if the bias voltage change from -0.063 to 0.048 V.

[0055] Region (ii) $V_{ds} < -0.063$ V

[0056] At this condition, J2 mainly contributes to the photoresponse due to a large enough reverse bias which extremely suppress the function of J1. Therefore, photoresponse can hardly be observed when polarization angle of incident light is 110°.

[0057] Region (iii) $V_{ds} > 0.048$ V

[0058] At this region, J1 dominates photoresponse due to a large enough forward bias. Similarly, no obvious photoresponse is observed when polarization angle of incident light is 0°. All these phenomena directly illustrate the excellent bias-switchable photoresponse in one unit.

[0059] FIG. 4E shows a plot of photocurrent (in nano-Amperes or nA) as a function of power (in micro-Watts or μW) illustrating the dependence of photocurrents on the incident power at V_{ds} = -0.1 V and V_{ds} = 0.1 V with angle of linear polarization (AoLP) of 0° and 110° according to various embodiments.

[0060] FIG. 4E displays the power dependence of photocurrents at different bias, where all the extracted photocurrents at different angle of linear polarization (AoLP) and different bias conditions exhibit linear dependence on the incident power, which is significant for the calibrating and computing reconstruction of this polarized photodetector applied for linear polarimetry.

[0061] In addition, the photoresponse speed is briefly assessed by the transient photoresponse depending on time. FIG. 4F shows a plot of normalized photoresponse as a function of time (in milliseconds or ms) illustrating a fast response speed of the device according to various embodiments, of which the rise time and fall time are ~200 μs. From the result, a fast photoresponse speed of ~200 μs was achieved in the device. Besides, for a relatively large dark resistance of ~100 MΩ by the set of unipolar barrier structure, a maximum

photovoltage responsivity (Rs) close to 200 V W^{-1}, a low noise equivalent power (NEP) of ~0.1 nW $Hz^{0.5}$ and high specific detectivity (D*) exceeding 10^7 Jones were obtained (see below under "Photovoltaic Effect In The Heterostructure" for details) at zero bias. All the above performances may permit the achievement of imaging application.

[0062] To demonstrate the function of polarimetry, bias-switchable polarization-resolved photoresponse of this photodetector are carefully explored. FIG. 5A is a plot of photocurrent (in nano-Amperes or nA) as a function of time (in seconds or s) illustrating the time dependence of photocurrents of the photodetector at -0.1V with the incident angle of linear polarization (AoLP) sweeping from 0º to 360º according to various embodiments. FIG. 5B is a plot of photocurrent (in nano-Amperes or nA) as a function of time (in seconds or s) illustrating the time dependence of photocurrents of the photodetector at 0.1V with the incident angle of linear polarization (AoLP) sweeping from 0º to 360º according to various embodiments. As shown in FIGS. 5A-B, the photocurrents depending on the AoLP from 0° to 360° show periodic increase and decrease. Furthermore, the polar plot of forward photocurrent I_{ph1} at 0.1 V and reverse photocurrent I_{ph2} at -0.1 V depending on the incident AoLP are extracted and shown in FIG. 5C. FIG. 5C shows polar plots of the forward bias 0.1V driven photocurrents and reverse bias -0.1V driven photocurrents excited by different incident angles of linear polarization (AoLP) from 0 to 360° according to various embodiments. The initial AoLP 0° is aligned along with the AC direction of the top b-AsP layer. From the polarization photoresponse, a rotation angle of 110° (or -70°) could be seen between the forward bias photocurrent and reverse bias photocurrent. The PR is ~55 and ~42 at -0.1 V and 0.1 V, respectively. Both of them can be well fitted by the function $I_{ph} = a * \cos(2\theta + \psi) + b$ with a phase difference $\Delta\psi$ of ~70°, which is consistent with the crystal orientations of the vdWH as shown in FIG. 3D. In addition, high polarization ratios (PR) of 55 and 42 are obtained at -0.1 V and 0.1 V, respectively. The function of bias on the J1 and J2 by the polarized photoresponse depending on AoLP at zero-

bias is further illustrated below (see "Dependence Of Polarization Photoresponse At Zero Bias").

[0063] Since the forward bias photocurrent I_{ph1} and reverse bias photocurrent I_{ph2} are independent, I_{ph1} and I_{ph2} can be assembled as shown in FIG. 5D. FIG. 5D is a plot of reverse bias photocurrent I_{ph} (in nano-Amperes or nA) as a function of forward bias photocurrent I_{ph} (in nano-Amperes or nA) illustrating two-dimensional (2D) plots of forward bias photocurrent I_{ph1} and reverse bias photocurrent I_{ph2} in cartesian coordinate system where the photocurrent pair (I_{ph1}, I_{ph2}) can be well fitted by a closed ellipse equation when the angles of linear polarization (AoLP) change from 0 to 180° according to various embodiments, of which the relationship enable the reconstruction of any unknown incident linear state of polarization (SOP). The incident power is ~155 μW at 4.6 μm. These dots (I_{ph1}, I_{ph2}) which represent the varied AoLP obey a regular closed elliptical path, as follows:

$$AI_{ph1}{}^2 + BI_{ph1}I_{ph2} + CI_{ph2}{}^2 + DI_{ph1} + EI_{ph2} + 1 = 0 \quad (1)$$

where *A*, *B*, *C*, *D* are the fitting parameters. That means each photocurrents pair corresponds to a fixed linear SOP. Combining the linear power dependence of photoresponse at a fixed bias, power calibration is also easy to be realized. Through the above discussion, it can be deduced that any unknown linear SOP of the detected light can be computed based on the calibrated polarized photoresponse I_{ph} [V_{bias}, θ] through the designed vdWH photodetector. This may be referred to as "double-shot" polarimetry for its convenient bias-selectivity operation mode, where only two signals obtained at forward and reverse biases are needed to determine the incident linear SOP without any other manipulation such as detector rotation or detector array. It is noted that any twisted angle except 0° and 90° is suitable to achieve the polarization photoresponse calibration (details provided below), which implies obvious improvement for full linear polarimetry. Moreover, polarized photoresponse under another two bias voltages (-0.5 V & 1 V) behave the same relationships for the I_{ph1} and I_{ph2}, where the polarization-resolved

photoresponse possess a phase difference of ~70°, too (see below under "Dependence Of Polarization Photoresponse At V_{ds} = -0.5 V and 1 V" for details). These results may illustrate that the flexibility in selection of bias and twisted angles for polarimetry by this type of bias-switchable unipolar barrier vdWH photodetector used for linear polarimetry.

[0064] Based on the high-performance detection and calibrating polarized-resolved function for MIR, the MIR polarimetry imaging is carried out to demonstrate the potential application in future on-chip polarimeter of this filter-free polarization-resolved photodetector. In usual, MIR detection behaves good invisibility in military reconnaissance or missile guidance. Here, obstructed media is applied to simulate the scenes where targets may be hidden in surroundings. FIG. 6A is a schematic of a home-built single-pixel scanning system according to various embodiments. The imaging target is covered by isotropic organic film-based visual obstruction to demonstrate the excellent ability of MIR polarization detection of the designed photodetector. A half-wave plate is applied for the modulation of incident SOP to simulate different surface states of the target "1" and "2" (see "Polarimetric Imaging" for details). The pre-set condition is 170° and 70°, respectively. FIG. 6B shows the light intensity images of the target at forward bias and reverse bias by the device according to various embodiments. It can be gathered from the images that the object occluded by the visual obstruction is number "1" and "2". FIG. 6C shows the computational reconstructed polarimetric image of the object described by the angles of polarization (AoP) according to various embodiments, from which more information of the target is obtained. Specifically, the angles of linear polarization (AoLP) of "1" around 170° and 70°of "2" are identical with the present conditions.

[0065] As shown in FIG. 6A, the detection part may only involve the position fixed single-pixel unit, without any optical polarization filter integration. For the target object, a half-wave plate modulated MIR illumination was set to simulate different SOP distribution of the target object. Two steps may be required to achieve the polarimetry imaging. First, establishment of

a three-dimensional current data tube (X, Y, Z), where X, Y represent the spatial position and Z stands for the bipolar bias conditions. Second, computation reconstruction by the calibrated I_{ph} [V_{bias}, θ] via mathematical calculation is processed according to the relationship below:

$$\theta = \cos^{-1}\left(I_{ph2}\right), \theta = \theta_1 \; or \; \theta_2 \quad (2)$$

$$I_{ph2} = 2.21 I_{ph1}^{0} - 27.31 \quad (3)$$

$$\Delta = I_{ph1} - I_{ph1}^{0} \quad (4)$$

where I_{ph1} and I_{ph2} are the probed signals, I_{ph1}^{0} is the calculated value. When Δ>0, the θ is equal to θ_1< 90°. Otherwise, Δ<0, the θ is equal to θ_2> 90°. FIG. 6B shows the light intensity imaging results at forward and reverse biases. As is seen, the hidden target is clearly recognized through the MIR imaging. Furthermore, the computing reconstructed polarimetric image is displayed in FIG. 6C, from which we could directly obtain the spatial distribution of the AoLP of target object. As is seen, there exists extremely different SOP between the number "1" and "2" in the polarimetric image, which could be hardly recognized by an intensity image. Then, the linear SOP of "1" and "2" could be described by Jones vector as $\begin{bmatrix} \cos\left(\frac{\pi}{18}\right) & 0 \\ 0 & \sin\left(\frac{\pi}{18}\right) \end{bmatrix} \begin{bmatrix} -1 \\ 1 \end{bmatrix}$ and $\begin{bmatrix} \sin\left(\frac{\pi}{9}\right) & 0 \\ 0 & \cos\left(\frac{\pi}{9}\right) \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix}$, respectively. According to the comparison between reconstructed results and pre-set experimental conditions, the successful demonstration of linear polarimetry may be identified by using the bias-switchable unipolar barrier photodetector. Considering the convenient "double-shot" operation mode, this device prototype could be well used in large-scale filter-free focal plane array in the future for MIR polarimetry. Apart from the linear SOP, circular SOP detection is also crucial, which may be achieved by a further optimized structure with chirality features.

[0066] Materials And Device Fabrication

[0067] The unipolar barrier heterostructure is established by mechanical exfoliation and dry-transfer technique depending on a home-built micro-mechanical transfer stage. The bottom b-AsP flake, middle WS_2 flake and top b-AsP flake are exfoliated and stacked layer by layer sequentially from bottom to top carried by the polydimethylsiloxane (PDMS). The b-AsP and WS_2 bulk are all purchased from the 2D semiconductors Co, Ltd. Then the electrodes (5 nm Cr/80 nm Au) are fabricated by electron-beam lithography, thermal evaporation disposition and standard lift-off process. The obtained device was encapsulated by the h-BN.

[0068] Material Characterization

[0069] The morphology of fabricated heterostructure device is characterized by an optical microscopy (Nikon) and finer surface topography is performed by atomic force microscope (Park NX10). The Raman spectra were characterized by the confocal Raman spectroscope (WItec alpha 300), where a 532 nm laser with light spot size of ~1 μm was focused on the sample. For the polarized Raman spectra, the sample rotate by 10° for each Raman spectrum illuminated by the excited laser with fixed polarization direction. The optical properties were measured by a FTIR spectroscopy (Bruker Vertex 80v and Hyperion 2000 microscope). For the polarized reflection and transmission spectra, a broadband polarizer was used to modulate the incident illumination by tungsten lamp source. The CaF_2 substrate and Au mirror are applied for the measurement of absorption. The relationship between reflection, transmission and absorption is $R + T + A = 100$ %.

[0070] Device Measurements

[0071] Electrical and optoelectrical measurements were processed by semiconductor parameter analyzer (Keysight B2912A) at room temperature and ambient surroundings. For the photoresponse, a MIR quantum cascade laser (Daylight Solution, MIRCat) was used and the incident MIR light was focused with a spot size of ~100 μm by a zinc selenide objective (focal length of 7.5 mm). For the polarized photoresponse, a half-wave plate was used to modulate

the SOP of incident light. The frequency dependence of device noise is measured by a lock-in amplifier (Zurich Instruments, HF2LI) with internally set frequency. The thermal power meter (OPHIR, Nova display-ROHS) is used for measuring the power of MIR illumination.

[0072] Polarimetric Imaging

[0073] The demonstration of polarimetric imaging is assisted by a home-built scanning system. The light source is Daylight MIRCat quantum cascade laser with output wavelength of 4.6 μm. The imaging target is covered by an organic P3HT (poly(3-hexylthiophene-2,5-diyl)) film to demonstrate the excellent MIR detection of the designed heterostructure device. As is known, the P3HT film is an isotropic VIS-NIR material, through which the target cannot be seen directly by human eyes. The photoresponse signal acquisition is completed by the designed device connected with the amplifier in Raman system, driven by the source meter. To achieve the single-pixel scanning imaging, an electric driven motorized stage was used. Considering the small spot compared to the imaging target, we take the program where the detector is fixed and the target is moving instead of the detector scanning scheme to complete the imaging process. Specially, to simulate different surface SOP of the imaging target, a half-wave plate was used to change the light SOP. In brief, the polarization of the target "1" is set as AoP of 170° and the polarization of the target "2" is set as AoP of 70°, respectively.

[0074] Optical Properties Of The b-AsP Absorber

[0075] In order to verify the crystal orientation and polarization absorption of b-AsP, polarized Raman spectra and polarized reflection & transmission are characterized. Considering the band gap of b-AsP closed to 0.2 eV, a CaF_2 substrate with high transmission from 400 nm to 7 μm is applied.

[0076] FIG. 7A shows an optical image of exfoliated black arsenic phosphorous (b-AsP) sample on a calcium difluoride (CaF_2) substrate according to various embodiments. The scale bar represents 30 μm. The thickness is measured by atomic force microscopy (AFM). FIG. 7B

is a plot of height (in nanometer) as a function of position (in micrometer) showing the height profile black arsenic phosphorous (b-AsP) sample on the calcium difluoride (CaF_2) substrate, with the inset showing the atomic force microscopy image of the sample according to various embodiments. The scale bar is 5 μm. The thickness of the black arsenic phosphorous (b-AsP) sample is measured to be about 300 nm. According to the empirical conclusion in previous reports, the long side of the exfoliated 2D material is often along with a certain crystal orientation. Moreover, the maximum absorption appears at the moment when the polarization direction of incident light is consistent with the armchair direction of b-AsP materials.

[0077] FIG. 7C shows a plot of intensity (in arbitrary units or a.u.) as a function of wavenumber (in per centimeter or cm^{-1}) illustrating the Raman spectra of the sample according to various embodiments. The Raman spectra indicate the crystal orientation of b-AsP where the Zigzag (ZZ) direction is along with the long edge of the sample and the armchair (AC) direction is perpendicular to the long edge. FIG. 7C shows the Raman spectra of b-AsP depend on the angle between the long side of sample and polarization direction of incident light with the angle increasing step of 10°. As is seen in the results, Raman peaks are located at ~260 cm^{-1}, ~360 cm^{-1}, ~440 cm^{-1} and ~460 cm^{-1}, which is consistent with the b-AsP reported in previous works. Furthermore, with the increase of the angle from 0° to 90°or -90°, the intensities of A_g^1 peak (~360 cm^{-1}) and gradually increase. The intensities of B_{2g} (~440 cm^{-1}) also increase while the intensities of A_g^2 (~460 cm^{-1}) first increases and then decreases.

[0078] The intensities ratio between A_g^1 and A_g^2 shown in FIG. 7D may help to verify the crystal orientation of b-AsP. FIG. 7D shows the intensity ratio of $I(A_g^1)/I(A_g^2)$ dependent on the different angles according to various embodiments. The diversification illustrates the long side of the sample is Zigzag (ZZ) direction as the mark in FIG. 7A. After the discrimination of crystal orientation, the optical properties are further characterized by the Fourier transform infrared (FTIR) spectrometer assisted by an infrared (IR) microscope.

[0079] FIG. 8A is a plot of transmission as a function of wavenumber (per centimeter or cm^{-1}) illustrating the polarized transmission of the black arsenic phosphorous (b-AsP) in the range of 1500 cm^{-1} to 4000 cm^{-1} according to various embodiments. FIG. 8B is a plot of reflection as a function of wavenumber (per centimeter or cm^{-1}) illustrating the polarized reflection of the black arsenic phosphorous (b-AsP) in the range of 1500 cm^{-1} to 4000 cm^{-1} according to various embodiments. FIGS. 8A-B show the polarized transmission and reflection spectra within the MIR wavenumber from 1500 cm^{-1} to 4000 cm^{-1}. The polarized absorption spectra are then calculated as shown in FIG. 8C. FIG. 8C is a plot of absorption as a function of wavenumber (per centimeter or cm^{-1}) illustrating the polarized absorption of the black arsenic phosphorous (b-AsP) in the range of 1500 cm^{-1} to 4000 cm^{-1} according to various embodiments.

[0080] It is noted that the energy band may be modulated by intrinsic defects which lead to an extended absorption range for b-AsP sample. Similar defect engineering functioned energy band modulation is reported in $PtSe_2$.

[0081] Construction Of Energy Band

[0082] In order to identify the conducting type and doping concentration, the electrical properties are measured for pure WS_2 and pure b-AsP as shown in FIGS. 9A-D. FIG. 9A shows a plot of current (in nano-Amperes or nA) as a function of drain-source voltage V_{ds} (in volts or V) illustrating the output curve of a tungsten disulfide (WS_2) field effect transistor (FET) according to various embodiments. FIG. 9B shows a plot of current (in nano-Amperes or nA) as a function of drain-source voltage V_{ds} (in volts or V) illustrating the output curve of a black arsenic phosphorous (b-AsP) field effect transistor (FET) according to various embodiments. FIG. 9C shows a plot of current (in nano-Amperes or nA) as a function of gate voltage V_g (in volts or V) illustrating the transfer curve of the tungsten disulfide (WS_2) field effect transistor (FET) according to various embodiments. FIG. 9D shows a plot of current (in nano-Amperes or nA) as a function of gate voltage V_g (in volts or V) illustrating the transfer curve of the black

arsenic phosphorous (b-AsP) field effect transistor (FET) according to various embodiments. The WS_2 and b-AsP FETs have thicknesses of ~6 nm and 45 nm, respectively, confirmed by atomic force microscopy (AFM).

[0083] FIG. 10A shows an atomic force microscopy (AFM) surface topography image of heterostructure photodetector according to various embodiments. The scale bar represents 5 μm. FIG. 10B shows a plot of height (in nanometers) as a function of position (in micrometers or μm) illustrating the height profile of the middle tungsten disulfide (WS_2) layer according to various embodiments. FIG. 10C shows a plot of height (in nanometers) as a function of position (in micrometers or μm) illustrating the height profile of the bottom black arsenic phosphorous (b-AsP) layer according to various embodiments. FIG. 10D shows a plot of height (in nanometers) as a function of position (in micrometers or μm) illustrating the height profile of the top black arsenic phosphorous (b-AsP) layer according to various embodiments.

[0084] As is seen, the WS_2 has typical N type conducting characteristics and the b-AsP has P type conducting characteristics. Then, the doping concentration could be evaluated by $\sigma = ne\mu$, where σ is conductivity, e is unit charge, n is carrier concentration and μ is carrier mobility. In addition, $\mu = \frac{dI_{ds}}{dV_g}\frac{L}{wC_iV_{ds}}$, which can be extracted from the transfer curves of FET. Assuming the completed ionization of carriers at room temperature, the surface densities n or p at $V_g = 0$ V of WS_2 and b-AsP could be calculated as 2.38×10^{11} cm^{-2} and 3.06×10^{13} cm^{-2}, respectively. The volume concentration n_v or p_v could be further calculated depending on the thickness of materials $n_v\ (p_v) = n(p)/h$. According to the thickness measurements of the heterostructure, the volume doping concentration of the three layers are 3.97×10^{17} cm^{-3}, 6.13×10^{18} cm^{-3} and 7.66×10^{18} cm^{-3}, respectively.

[0085] Photovoltaic Effect In The Heterostructure

[0086] To further demonstrate the photoresponse mechanism, the photovoltages and photocurrents at 0 V were extracted from FIGS. 4D-E and shown in FIGS. 11A-F. FIG. 11A

shows a plot of photovoltage V_{ph} (in milli-Volts or mV) as a function of power (in micro-Watts or μW) illustrating the dependence of photovoltage on incident power of light with polarization states of 0º and 110º according to various embodiments. FIG. 11B shows a plot of photocurrent I_{ph} (in nano-Amperes or nA) as a function of photovoltage V_{ph} (in milli-Volts or mV) illustrating the relationship between short circuit current and open circuit voltage due to incidence of light at 0º according to various embodiments. FIG. 11C shows a plot of photocurrent I_{ph} (in nano-Amperes or nA) as a function of photovoltage V_{ph} (in milli-Volts or mV) illustrating the relationship between short circuit current and open circuit voltage due to incidence of light at 110º according to various embodiments. The plotted data in FIGS. 11B-C may be well fitted by the classical theory for photodiode. FIG. 11D is a plot of responsivity (in volts per Watt or V/W) as a function of power (in micro-Watts or μW) illustrating the dependence of responsivity on the incident power at 0 V at state of polarization (SOP) of 0º and 110º according to various embodiments. FIG. 11E shows a plot of noise (in nano-Volts per Hertz square-root or nV $Hz^{-0.5}$) as a function of frequency (in Hertz or Hz) illustrating the measured frequency dependence on noise according to various embodiments. FIG. 11F shows a plot of noise equivalent power NEP (in Watts Hertz square-root or W $Hz^{0.5}$) / specific detectivity D* (in centimeter Hertz square-root per Watt or cm $Hz^{0.5}$ W^{-1}) as a function of power (in micro-Watts or μW) illustrating the dependence of NEP and D* at states of polarization of 0º and 110º according to various embodiments.

[0087] The results show that the photovoltages at 0° and 110° tend to saturate on the increase of power. The V_{oc} and I_{sc} in a two-dimensional plot can be well fitted by the followed formula for both illuminations at 0° and 110°,

$$V_{oc} = \frac{\mathrm{nkT}}{\mathrm{e}} \ln\left(\frac{I_{sc}}{\mathrm{I_0}} + 1\right) \quad (5)$$

where n is the ideality factor, k is the Boltzmann constant, e is the elementary charge, T is the temperature and I_0 is the reverse saturation current. It intuitively illustrates the photovoltaic

effect based on the back-to-back junctions J1 and J2 dominate the photoresponse of this designed twisted unipolar barrier vdWH at 0 V.

[0088] In addition, specific detectivity (D*) is measured, which is decided by the noise level and responsivities $D^* = (A)^{0.5}/NEP$, where A is active area and NEP is the noise equivalent power. Therefore, frequency dependent noises are measured firstly by lock-in amplifier with internal setting frequency as reported by previous works. 1/f noise at low frequency (<1 kHz) and Johnson noise (>1 kHz) dominate the noise level, respectively. Considering a fast response speed of ~200 μs, the device could operate at 1 kHz normally. Hence, the NEP and D* corresponding to a low noise level under 1kHz, i.e., ~10 nV $Hz^{-0.5}$ may be calculated. As a result, low NEP less than 0.1 nW $Hz^{0.5}$ is obtained and high D* surpassing 10^7 Jones is realized. In general, this heterostructure may behave with low noise levels and high detectivity at room temperature in MIR range although the responsivity is relatively weak. It may be attributed that the operational wavelength is very close to the cut-off wavelength of b-AsP absorber limited by bandgap. Further optimization could be processed by updating another anisotropic absorber with narrower bandgap than b-AsP.

[0089] Dependence Of Polarization Photoresponse At Zero Bias

[0090] Due to the formation of back-to-back PN junction in the three layer-vdWH, photocurrents of opposite polarities from the two junctions would appear. Therefore, a net current would be zero in an ideal back-to-back PN junction without polarization absorption under illumination. However, in this work, the optical properties of these two junctions may be different. In brief, there may be obvious absorption difference between the two junctions which is determined by the SOP of incident illumination. More absorption would contribute to more photocurrent. Therefore, with the sweeping of incident SOP from 0 to 360°, the two junctions may dominate the photoresponse alternately, which results in a bipolarity photocurrent as shown in FIGS. 12A-B.

[0091] FIG. 12A shows a plot of photocurrent (in nano-Amperes or nA) as a function of angle (in degrees or º) illustrating the bipolarity dependence on the state of polarization (SOP) at bias voltage of 0V according to various embodiments. FIG. 12A is extracted from FIG. 12B. FIG. 12B shows a plot of drain current (in nano-Amperes or nA) as a function of time (in seconds or s) illustrating the time-dependence of the photoresponse according to various embodiments. The incident linear polarization state rotates by 10° for every light on-off cycle.

[0092] Due to the bias voltage, one of the junctions would be forward and another one would be reversed, which will weaken the weights of the forward biased junction in photoresponse process as discussed earlier. That may cause the decrease and disappearance of bipolarity photoresponse.

[0093] Theoretical Study Of Twisted Angle Dependence Of Photoresponse

[0094] Originating from the natural linear dichroism, photocurrents at both forward and reverse bias dependent on the incident SOP could be described as a trigonometric function equations $I_{pc} \propto \cos 2\theta$, as shown earlier. Because of the consistency between anisotropic optical properties and photoresponse performance under the change of SOP, the phase difference of the bias selective photoresponse could be well controlled by the twisted angle ψ of bottom b-AsP and top b-AsP. Therefore, the rotation angle dependent polarized photoresponse at ±bias may be predicted.

[0095] The bottom As-P layer is assumed to be fixed and the initial polarization state 0° is aligned with the maximum photoresponse at forward bias (i.e., the bottom layer as an absorber). Then the top layer b-AsP is rotated from 0° to 90°. FIG. 13A shows a plot of photoresponse (in arbitrary units or a.u.) as a function of state of polarization (SOP) angle (in degrees or º) illustrating the theoretical polarized photoresponse at different bias depending on the bottom layer and the top layer according to various embodiments. FIG. 13B shows a plot of photoresponse (in arbitrary units or a.u.) as a function of state of polarization (SOP) angle (in

degrees or º) illustrating the theoretical polarized photoresponse at different angles between the bottom layer and the top layer according to various embodiments. Then, the photocurrents pairs (I_{ph1}, I_{ph2}) could be extracted in a two-dimensional plot by sweeping the SOP as shown in FIG. 13C. FIG. 13C is a plot of the top photoresponse (in arbitary units or a.u.) as a function of the bottom photoresponse (in arbitary units or a.u.) illustrating the photoresponse with bottom black arsenic phosphorous (b-AsP) layer as absorber at forward bias and top black arsenic phosphorous (b-AsP) layer as absorber at reverse bias, respectively according to various embodiments. From the results, it can be seen that a series of rotation angles except for 0° and 90° may be employed for SOP probing.

[0096] Dependence Of Polarization Photoresponse At V_{ds} = -0.5 V and 1 V

[0097] FIG. 14A shows polar plots of the forward bias 1V driven photocurrents and reverse bias -0.5V driven photocurrents excited by different incident angles of linear polarization (AoLP) from 0 to 360° according to various embodiments. The initial polarization states 0° is aligned along with the AC direction of the top b-AsP layer.

[0098] FIG. 14B is a plot of reverse bias photocurrent I_{ph} (in nano-Amperes or nA) as a function of forward bias photocurrent I_{ph} (in nano-Amperes or nA) illustrating two-dimensional (2D) plots of forward bias photocurrent I_{ph1} and reverse bias photocurrent I_{ph2} in cartesian coordinate system where the photocurrent pair (I_{ph1}, I_{ph2}) can be well fitted by a closed ellipse equation when the angles of linear polarization (AoLP) change from 0 to 180° according to various embodiments when the photodetector is at -0.5V and 1V bias voltage and illuminated with a 4.6 μm laser.

[0099] FIG. 14C is a plot of photocurrent (in nano-Amperes or nA) as a function of time (in seconds or s) illustrating the time dependence of photocurrents of the photodetector at -0.5V with the incident angle of linear polarization (AoLP) sweeping from 0º to 360º according to various embodiments. FIG. 14D is a plot of photocurrent (in nano-Amperes or nA) as a function

of time (in seconds or s) illustrating the time dependence of photocurrents of the photodetector at 1V with the incident angle of linear polarization (AoLP) sweeping from 0º to 360º according to various embodiments. The incident linear polarization state rotates by 10° for every light on-off cycle.

[00100] Various embodiments may relate to a twisted unipolar barrier photodetector with a twisted vdWH, which could be used for MIR linear polarimetry. One example may be a b-AsP/WS_2/b-AsP stacked arrangement. By the careful design of band structure where small barrier for electrons and high barrier for holes are constructed, two different bias-switchable polarized photocurrent signals may be obtained in a single device. Then, an unknown incident linear SOP may be detected by this designed photodetector with natural anisotropy and without any additional plasmon nanostructures or metasurfaces. Based on this function, linear polarimetric imaging may be demonstrated. All the results show that this designed polarized photodetector may pave a new way towards the on-chip polarimeter in the future.

Claims

1. A photodetector comprising:

a first layer of a first material having a first crystal orientation;

a second layer of the first material having a second crystal orientation different from the first material of the first layer; and

a third layer of a second material between the first layer and the second layer;

wherein a bandgap of the second material is larger than a bandgap of the first material;

wherein the first crystal orientation and the second crystal orientation are non-perpendicular and non-parallel to each other;

wherein the photodetector, under a first voltage bias between the first layer and the second layer, is configured to generate a first photocurrent upon incidence of a first polarized light having a first polarization angle onto the photodetector; and

wherein the photodetector, under the first voltage bias between the first layer and the second layer, is configured to generate a second photocurrent of a magnitude different from a magnitude of the first photocurrent upon incidence of a second polarized light having a second polarization angle different to the first polarization angle onto the photodetector.

2. The photodetector according to claim 1,

wherein the photodetector is configured such that an energy barrier for holes is higher than an energy barrier for electrons.

3. The photodetector according to claim 2,

wherein the energy barrier for holes is more than 0.5 eV.

4. The photodetector according to claim 1,

wherein the photodetector is configured such that an energy barrier for electrons is higher than an energy barrier for holes.

5. The photodetector according to claim 4,

wherein the energy barrier for electrons is more than 0.5 eV.

6. The photodetector according to any one of claims 1 to 5,

wherein a difference between the first polarization angle and the second polarization angle is between 0 degree and 180 degrees.

7. The photodetector according to any one of claims 1 to 6,

wherein the photodetector, under a second voltage bias between the first layer and the second layer, the second voltage bias having a polarity different from a polarity of the first voltage bias, is configured to generate third photocurrent of a magnitude different from a magnitude of the first photocurrent upon incidence of the first polarized light onto the photodetector.

8. The photodetector according to any one of claims 1 to 7,

wherein a photocurrent pair comprising a forward bias current under a predetermined forward biasing voltage and a reverse bias current under a

predetermined reverse biasing voltage corresponds to a fixed linear state of polarization.

9. The photodetector according to any one of claims 1 to 8,

wherein the first material is black arsenic phosphorous (b-AsP); and

wherein the second material is tungsten disulfide (WS_2).

10. The photodetector according to any one of claims 1 to 9,

wherein the photodetector has a van der Waals heterostructure.

11. A method of forming a photodetector, the method comprising:

forming a first layer of a first material having a first crystal orientation;

forming a second layer of the first material having a second crystal orientation different from the first material of the first layer; and

forming a third layer of a second material between the first layer and the second layer;

wherein a bandgap of the second material is larger than a bandgap of the first material;

wherein the first crystal orientation and the second crystal orientation are non-perpendicular and non-parallel to each other;

wherein the photodetector, under a first voltage bias between the first layer and the second layer, is configured to generate a first photocurrent upon incidence of a first polarized light having a first polarization angle onto the photodetector; and

wherein the photodetector, under the first voltage bias between the first layer and the second layer, is configured to generate a second photocurrent of a magnitude different from a magnitude of the first photocurrent upon incidence of a second polarized light having a second polarization angle different to the first polarization angle onto the photodetector.

12. The method according to claim 11,

wherein the photodetector is configured such that an energy barrier for holes is higher than an energy barrier for electrons.

13. The method according to claim 12,

wherein the energy barrier for holes is more than 0.5 eV.

14. The method according to claim 11,

wherein the photodetector is configured such that an energy barrier for electrons is higher than an energy barrier for holes.

15. The method according to claim 14,

wherein the energy barrier for electrons is more than 0.5 eV.

16. The method according to any one of claims 11 to 15,

wherein a difference between the first polarization angle and the second polarization angle is between 0 degree and 180 degrees.

17. The method according to any one of claims 11 to 16,

wherein the photodetector, under a second voltage bias between the first layer and the second layer, the second voltage bias having a polarity different from a polarity of the first voltage bias, is configured to generate third photocurrent of a magnitude different from a magnitude of the first photocurrent upon incidence of the first polarized light onto the photodetector.

18. The method according to any one of claims 11 to 17,

wherein a photocurrent pair comprising a forward bias current under a predetermined forward biasing voltage and a reverse bias current under a predetermined reverse biasing voltage corresponds to a fixed linear state of polarization.

19. The method according to any one of claims 11 to 18,

wherein the first material is black arsenic phosphorous (b-AsP); and

wherein the second material is tungsten disulfide (WS_2).

20. The method according to any one of claims 11 to 19,

wherein the photodetector has a van der Waals heterostructure.