(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
3 January 2014 (03.01.2014)

WIPO | PCT

(10) International Publication Number
WO 2014/002082 A2

(51) International Patent Classification:
H01L 31/101 (2006.01)

(21) International Application Number:
PCT/IL2013/050521

(22) International Filing Date:
18 June 2013 (18.06.2013)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
220676 28 June 2012 (28.06.2012) IL

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *of inventorship (Rule 4.17(iv))*

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

WO 2014/002082 A2

(54) Title: PHOTODETECTOR DEVICE

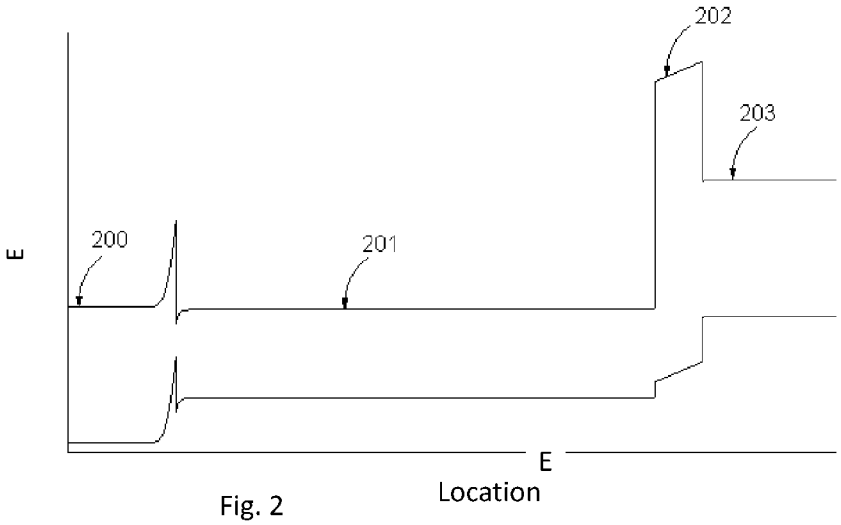


Fig. 2

(57) Abstract: The present disclosure provides a photodetector device comprising a heterostructure comprising a sequence of a first contact layer, an absorbing layer, a barrier layer, and a second contact layer. The absorbing layer comprises (or is made of/consists of) a ternary alloy of InPSb; an energy bandgap of the barrier layer is wider than the absorbing layer and is configured so that the conduction band of the heterostructure presents a discontinuity with the absorbing layer; the contact layer, the barrier layer, and the first and second contact layers are configured so that substantially no offset appear at the valence band.

PHOTODETECTOR DEVICE

TECHNOLOGICAL FIELD

The present disclosure relates to photodetectors for sensing light. More particularly, the present disclosure relates to a photodiode structure with reduced dark current.

BACKGROUND

Traditionally, in detector technology, the infrared band is divided to Near IR (NIR) between 0.75μm and 1.1μm, Short Wavelength IR (SWIR) between 1.1μm and 2.5μm, Mid Wave IR (MWIR) between 3μm and 5μm and Long wave IR (LWIR) between 8μm and 14μm.

SWIR detectors are used for various civilian and military applications including night vision, gas monitoring and other. The common use of the SWIR spectral regime is between 0.9μm and 1.7μm as enabled by InGaAs photo-diodes with Indium content of 53% lattice matched to InP (Indium Phosphide) substrate. Extended wavelength SWIR photodiodes are available with strained InGaAs (Indium Gallium Arsenide) alloys that contain higher contents of Indium. Another available sensing technology for the SWIR spectral regime is with HgCdTe (Mercury Cadmium Telluride) p-n junction diodes. More recently, Sidhu, R.; Ning Duan; Campbell, J.C.; Holmes, A.L., Jr. have presented in "A long-wavelength photodiode on InP using lattice-matched GaInAs-GaAsSb type-II quantum wells," *Photonics Technology Letters, IEEE*, vol.17, no.12, pp. 2715- 2717, Dec. 2005, a structure of type II superlattice with InGaAs/GaAsSb (Gallium Arsenide Antimonide) thin layers lattice matched to InP as an extended wavelength SWIR photodetector in a p-n junction configuration.

A new class of MWIR detectors has recently been developed as described for example in United States Patent US 7,687, 871. Such detectors comprise MWIR absorption n-type semiconductor, a large bandgap undoped barrier layer and a second thin n-type layer. The barrier bandgap is larger than that of the absorption or contact

layers. The thickness of the absorption n-type layer is about an optical absorption length or two. The barrier layer is thick enough so that there is negligible electron tunneling through it. The potential height of the barrier layer is such that there is negligible thermal excitation of majority carrier over it. The second n-type layer serves as a contact layer. In operation, metal contacts are applied to the n-type layers and a potential difference is applied to these metal contacts.

GENERAL DESCRIPTION

The inventor has found an improved configuration of an IR detector which allows close to room temperature operation and limits the dark current. In particular, it can allow operation of extended wavelength Short Wavelength Infra Red detectors at close to room temperature.

Reducing the detector dark current increases the dynamic range of the system, improves the signal to noise ratio of the detection, and decreases the residual non uniformity of detector array. Further, the new detector may not require cooling and therefore enables decreasing the system volume, weight, cost and power consumption, thus allowing its use in a variety of applications.

In a first broad aspect, the present disclosure provides a photodetector device comprising a heterostructure comprising a sequence of a first contact layer, an absorbing layer, a barrier layer, and a second contact layer. The absorbing layer comprises (or is made of/consists of) a ternary alloy of InPSb; an energy bandgap of the barrier layer is wider than the absorbing layer and is configured so that the conduction band of the heterostructure presents a discontinuity with the absorbing layer; the contact layer, the barrier layer, and the first and second contact layers are configured so that substantially no offset appear at the valence band.

In some embodiments, the absorbing layer is lattice matched to at least one of the first contact layer, the barrier layer and the second contact layer.

In some embodiments, the first contact layer, the second contact layer and the absorbing layer comprise (or are made of/consist) doped semiconductors.

In some embodiments, the barrier layer comprises (or is made of/consists) undoped intrinsic semiconductor.

In some embodiments, a Sb content of the ternary alloy of InPSb is configured so as to be capable of absorbing infrared radiations of a wavelength up to 2.5 μm cut-off wavelength at room temperature.

In some embodiments, the first contact layer and the absorbing layer are doped of the same conductivity type.

In some embodiments, the second contact layer and the absorbing layer are doped of same conductivity type.

In some embodiments, the second contact layer and the absorbing layer are doped of opposite conductivity type.

In some embodiments, the absorbing layer is lattice matched to the barrier layer and to the first and second contact layers.

In some embodiments, the first contact layer comprises GaSb grown on a GaSb substrate.

In some embodiments, the Sb content in the ternary alloy InPSb of the absorbing layer is of about 37%.

In some embodiments, the barrier layer comprises a ternary alloy of AlAsSb.

In some embodiments, the Sb content in the ternary alloy of the AlAsSb is about 92%.

In some embodiments, the second contact layer comprises GaSb.

In a second broad aspect, the present disclosure provides a photodetector matrix comprising an array of photodetectors as previously described. At least some of the photodetectors of the photodetector matrix share a common first contact layer, a common absorption layer and a common barrier layer.

In a third broad aspect, the present disclosure provides a night vision system for imaging an object, comprising a photodetector matrix as previously described; an optical system configured for collecting light and focusing the collected light onto the photodetector matrix; and a spectral filter located in an optical path of light propagating toward the photodetector matrix, said spectral filter configured and operable to selectively filter out light of wavelength shorter than a predetermined value, thereby gradually shifting operation of the night vision system from mostly reflection mode to a combined reflection and thermal mode to allow the night vision system to detect light reflected from and emitted by the object being imaged.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the disclosure and to see how it may be carried out in practice, embodiments will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

Fig. 1 illustrates schematically a photosensitive heterostructure used in a detector device according to an embodiment of the present disclosure.

Fig. 2 is a band diagram illustrating schematically the energy levels of the valence and conduction bands in dark condition for a heterostructure device for photodetection according to an embodiment of the present disclosure.

Fig. 3 is a band diagram illustrating schematically the energy levels of the valence and conduction bands in illumination condition for a heterostructure device for photodetection according to an embodiment of the present disclosure.

Fig. 4 is a block diagram illustrating schematically steps of a process for fabricating a heterostructure device for photodetection according to an embodiment of the present disclosure.

Fig. 5 illustrates schematically a photodetector array in an embodiment of the present disclosure.

DETAILED DESCRIPTION OF EMBODIMENTS

Described herein are some examples of heterostructure devices for photodetection and methods of fabricating said devices according to the invention.

In the following detailed description, specific details are set forth in order to provide a thorough understanding of the subject matter. However, it will be understood by those skilled in the art that some examples of the subject matter may be practiced without these specific details. In other instances, well-known methods, procedures and components have not been described in detail so as not to obscure the description.

As used herein, the phrase "for example," "such as", "for instance" and variants thereof describe non-limiting examples of the subject matter.

Reference in the specification to "one example", "some examples", "another example", "other examples", "one case", "some cases", "another case", "other cases" or variants thereof means that a particular described feature, structure or characteristic is included in at least one example of the subject matter, but the appearance of the same term does not necessarily refer to the same example.

It should be appreciated that certain features, structures and/or characteristics disclosed herein, which are, for clarity, described in the context of separate examples, may also be provided in combination in a single example. Conversely, various features, structures and/or characteristics disclosed herein, which are, for brevity, described in the context of a single example, may also be provided separately or in any suitable sub-combination.

Fig. 1 illustrates a heterostructure based device for photodetection (also referred to hereinafter as the photodetection device) in an embodiment of the present disclosure. The photodetection device **1** comprises a heterostructure including a first contact layer **12**, an absorbing layer **13**, a barrier layer **14** and a second contact layer **15**.

The first and second contact layers **12, 15** may be used to apply a voltage thereto to create an electric field within the absorbing layer **13** and the barrier layer **14**. The first contact layer **12** and the second contact layer **15** may be strongly doped so as to allow ohmic contact. In operation, a negative bias may be applied to the second contact layer **15** with respect to the first contact layer **12** for reversely bias the junction between the absorbing layer **13** and the barrier layer **14**. The first and second contact layers **12**, **15** may be obtained by appropriate growing methods on a respective substrate as described in more details hereinafter. In an embodiment, the first and second contact layers may be lattice matched to the substrate so as to limit growing defects in said layers. Indeed, one of the major contributors to dark current is generation recombination (G-R) centers located in the material. In many cases the source for those recombination centers is crystal defects generated due to the mismatch between the lattice constants of the device layers and as a result of epitaxial growth imperfections. The density of those recombination centers can be reduced in a lattice matched structure.

The absorbing layer **13** may be used to absorb a predetermined radiation. The energy gap between the valence and conduction bands determines a cut off wavelength of the photodetection device. The absorbing layer **13** may comprise (or may consist of) an alloy of InPSb (Indium Phosphide Antimonide). The width of the absorbing layer may be in the order of the optical absorption length in the alloy at extended SWIR wavelengths. In an embodiment, the content of Sb (Antimonide) in the InPSb alloy is of around 37% so that the bandgap of the absorbing layer **13** is of about 0.5eV, thereby enabling to sense radiation with a wavelength up to 2.5 μm. Indeed, the wavelength and the energy bandgap are linked by the following relation:

$$\lambda_{co} \sim 1.24/E_g,$$

wherein λ_{co} is the cut-off wavelength and E_g is the energy bandgap. In the previous example, the aforementioned relation provides a cut-off wavelength of about 2.48μm at room temperature. The absorbing layer **13** may be grown on top of the first contact layer by appropriate growing methods. The absorbing layer **13** may be lattice matched to the substrate and to the first contact layer **12**. The energy bandgap of the first contact layer (and of the substrate if the substrate is not removed) may be wider than that of the absorbing layer so as to be transparent for enabling illumination through the first contact layer (and the substrate in case it is not removed) i.e. back illumination configuration. The substrate and the first contact layer may be made of GaSb which is transparent from 1.8 μm and above.

The barrier layer **14** may comprise (or consist of) an undoped semiconductor designed so as to block the majority carriers while not preventing a minority carrier flow. In other words in case of n type absorber, the barrier layer **14** may be configured so that an energy bandgap of the barrier layer **14** is wider than that of the absorbing layer **13**, and the conduction band of the heterostructure presents a discontinuity with the absorbing layer **13**. Further, the heterojunctions between barrier, absorbing and contact layers may be configured so that no offset appears at the valence band. The configuration may be such that the absorbing layer **13** is the layer of the narrowest bandgap in the structure. The thickness of the barrier layer **14** may be configured to prevent tunneling of majority carriers through it.

Two main mechanisms contribute to dark current of a photo-diode. The first mechanism - diffusion, generated when charge carriers are thermally excited within a diffusion length from the depletion region of the p-n junction. This mechanism is a band to band transition process and therefore it is proportional to $\exp(-E_g/kT)$, wherein E_g is the energy gap, k is Boltzman's constant and T is the absolute temperature. The second mechanism of dark current generation is due to generation and recombination of charge carriers through traps located within the semiconductor forbidden energy gap. The rate of this mechanism known as Shockley-Reed-Hall (SRH) process or G-R is proportional to $\exp(-E_g/nkT)$ where n is an ideality factor usually found to be 2. The G-R process is efficient in the presence of depletion region of a p-n junction due to high occupation of mid gap states. It also increases with the reverse bias applied over the p-n junction. In the heterostructure for photodetection of the present disclosure, the device may be

designed so as not to provide a depletion layer within the absorption layer. The depletion layer is formed within the barrier layer **14** enables to limit the G-R dark current. Indeed, the bandgap of the barrier layer **14** is sufficiently high for the G-R current to be negligible. In this structure, the G-R current is reduced significantly and this way the device can be operated at higher temperature, and/or lower noise, higher dynamic range and better device uniformity. In addition, since, after the G-R dark current reduction, the dominant dark current mechanism is associated with diffusion which is not sensitive to bias change, an increased bias can be applied over the device for better photo-current response.

In a specific but not limiting example, a heterostructure device for photodetection includes the first contact layer **12** being n-doped GaSb layer; the absorbing layer **13** being slightly n-doped $InP_{0.63}Sb_{0.37}$ layer; the barrier layer being an intrinsic (i.e. with no specific doping) $AlAs_{0.08}Sb_{0.92}$ layer; and the second contact layer being a p- or n-doped GaSb layer. More specifically, an example of a heterostructure device for photodetection is hereinafter provided as an example of a lattice matched structure able to sense SWIR radiation. The substrate which is chosen to perform the growth of the heterostructure thereon (and removed after the structure formation) may be GaSb; the first contact layer **12** may be formed on the substrate by a 1 μm layer of n-doped GaSb with a doping density of 6e17 cm^{-3}; the absorbing layer **13** may be formed on the first contact layer **12** by a 3 μm layer of n-doped $InP_{0.63}Sb_{0.37}$ with a doping density of 1e16 cm^{-3}; the barrier layer may be formed on top of the absorbing layer as a 0.1 μm layer of intrinsic $AlAs_{0.08}Sb_{0.92}$; and the second contact layer may be formed of a 1 μm layer of p-doped GaSb with a doping density of 3e18 cm^{-3}.

As indicated above, the lattice matching between the layers in the heterostructure as well as to that of the substrate on which the layers are grown is an important feature affecting the device operation, e.g. reducing the dark current. The use of the above described heterostructure provides for as high as desired lattice match and effective absorption of the desired wavelength band. The wavelength range 1.8-2.5 microns might be of special interest to enable concurrent or sequential detection of signals associated with reflection of ambient IR radiation from an object being imaged and also IR emission from said object. In order to address said wavelength band, a detection system comprising the above-described photodetector may further include an appropriate spectral filter filtering out radiations with a wavelength inferior to 1.8

microns. In another embodiment, the first contact layer and/or the substrate (if it is not removed) may filter the radiations with a wavelength inferior to a predetermined value, for example 1.8 microns.

Figs. 2 and **3** illustrate, respectively in dark condition and in operation condition, the energy levels of the valence and conduction bands of a heterostructure device for photodetection according to an embodiment of the present disclosure. **Fig. 3** further illustrates electron-hole circulation in operation condition. The heterostructure device for photodetection corresponding to the exemplified band diagram may be similar to the abovementioned example. The energy levels of the valence and conduction bands of the first contact, absorbing, barrier and second contact layers are respectively generally referenced **200**, **201**, **202** and **203**. The absorbing layer may consist of n-type InPSb lattice matched to GaSb substrate with energy band gap of E_g~0.5eV at room temperature. The thickness of the absorbing layer **201** may be in the order of the optical absorption length in this alloy, at extended SWIR wavelengths. In one side of the absorbing layer indicated by label **200** an n-type GaSb contact may be located, while in the other side of the absorption layer a barrier indicated by label **202** may be located. The barrier **202** may consist of an un-doped alloy of AlAsSb (Aluminium Arsenide Antimonide) layer lattice matched to GaSb. The barrier bandgap may be designed to block the flow of thermally generated majority carriers, while allowing the flow of minority carriers (holes in this example). The thickness of the barrier **202** is designed to prevent tunneling of majority carriers through the barrier. On the other side of the barrier **202,** contact layer indicated by label **203** may be located. This contact layer may consist of p-type GaSb. It is noted that a sort of "pulse" may be seen on Figs. 2 and 3 at the interface between the first contact layer and the absorbing layer. This "pulse" result from band bending caused naturally due to doping profile and indicates that charge carriers are accumulated at the absorber interface within the contact-absorber heterojunction, while the contact layer interface is depleted.

In order to arrange the Fermi level in appropriate manner, a negative bias over the second contact layer **203** may be applied with respect to the first contact layer **200**. In this manner, the Fermi level at the contact layer **203** would be higher than the Fermi level at the absorption layer **201**. As illustrated in **Fig. 3**, when a photon with appropriate energy is being absorbed, the device generates an electron **204** – hole **205** pair. The minority carriers are further swept towards the contact layer **203** as illustrated

by label **206**. Since the valence band of the layers is arranged in a way that there is no potential barrier to the minority carriers (holes), they are flowing un-impeded towards the second contact layer **203**. The generated majority carriers (electrons) are swept towards the first contact layer **200**. It is to be noted that a similar structure can be applied with an n-type second contact layer (instead of a p-type second contact layer). In this case, the negative bias applied over the contact layers may be higher.

The non uniformity of an array of devices according to the previously described structure may be reduced as compared to the current techniques. The reduction in the non uniformity may be due to dominance of diffusion dark current over G-R dark current and to the independency of the diffusion dark current on the applied bias. Since in this device no appreciable G-R current is expected, fluctuation of the applied bias will not change the dark current and therefore will not affect the uniformity of dark currents across different devices. In addition, the barrier **202** may function as an inherent passivation layer that prevents currents generated at surface states and improves uniformity of an array of devices.

Fig. 4 describes steps of a manufacturing process for manufacturing a heterostructure device for photodetection according to an embodiment of the present disclosure. In a first step **S101**, a substrate is provided. There is a limited amount of materials that can be used as substrates for growing the semiconductor layers of the photodetector because of practical constraints. The substrate may be preferably chosen so as to lattice match the absorbing layer which is chosen according to the wavelength to be sensed. In a second step **S102**, a first contact layer may be grown on the substrate for example by epitaxial growth In order to avoid lattice mismatch, the first contact layer may be formed by the same material as the substrate. The first contact layer may be doped so as to have desired electrical conductivity. In a third step **S103**, the absorbing layer may be grown on the first contact layer. The absorbing layer may be made of a ternary alloy of III-V semiconductors. As explained above, it may be configured so as to sense radiation up to a predetermined cut-off wavelength depending on the energy bandgap of the ternary alloy. The absorbing layer may preferably comprise or consist of a ternary alloy of InPSb. The choice of the absorbing layer material may in fact direct the choice of the substrate since it is preferable to have lattice matched layers in the structure. In a fourth step **S104**, a barrier layer may be grown on the absorbing layer for example by epitaxial growth. Preferably, the absorbing layer

may be lattice matched to the other previously grown layers. In a fifth step **S105**, a second contact layer may be grown on top of the barrier layer, for example by epitaxial growth. Preferably, the second contact layer may be lattice matched to the other layers. For example, the second contact layer may be made of the same material than the substrate. In a further step (not shown), the substrate may be etched off the structure and the resulting structure may be shaped into a sensor by further etching as described in more details below.

Fig. 5 illustrates a photodetector array **100** in an embodiment of the present disclosure. The photodetector array **100** may comprise n x m photodetectors (n and m being integers). The photodetectors forming the photodetector array **100** may be arranged in a rectangular shape, circular shape or any other of planar or spatial arrangement. Same elements on **Fig. 5** and **Fig. 1** are given same numeral references. For the sake of conciseness, only the additional features with regard to the photodetectors previously described are discussed in the following. On **Fig. 5**, an embodiment with an array of three photodetectors is illustrated. The photodetectors share a common first contact layer **120**, a common absorbing layer **130**, and a common barrier layer **140**. Further, at least some of the photodetectors comprise a separate second contact layer **15** so as to form independent pixels. As explained before, the second contact layer is similar to the second contact layer **15** described with reference to **Fig. 1**. The properties of the common first contact layer **120**, common absorbing layer **130**, a common barrier layer **140** are also similar respectively to the first contact layer, absorbing layer and barrier layer previously described. Moreover, the design of said layers is such that said layers are common to at least some of the photodetectors of the photodetector array **100**. In order to manufacture such photodetector array, it is possible for example to firstly grow on the surface of a substrate a first contact layer, an absorbing layer, a barrier layer, and a second contact layer and to secondly etch the second contact layer so as to form several photodetectors sharing a common first contact layer, absorbing layer and barrier layer. Further etching may be required in order to place a first contact (not shown) on a peripheral area of the common first contact layer **120** and one or more pixel contact (not shown) may be placed on at least some of the photodetectors resulting from the etching operation. A passivation layer may also be deposited in order to reduce dark current generated by surface defects. Such

a photodetector array **100** may be useful for imaging purposes and may be adapted to commercially available readout integrated circuits.

The above examples and description have of course been provided only for the purpose of illustration, and are not intended to limit the invention in any way. As will be appreciated by the skilled person, the invention can be carried out in a great variety of ways, employing more than one technique from those described above, all without exceeding the scope of the invention.

CLAIMS:

1. A photodetector device comprising a heterostructure comprising a sequence of a first contact layer, an absorbing layer, a barrier layer, and a second contact layer, wherein:

- the absorbing layer comprises a ternary alloy of InPSb;
- an energy bandgap of the barrier layer is wider than the absorbing layer and is configured so that the conduction band of the heterostructure presents a discontinuity with the absorbing layer;
- the contact layer, the barrier layer, and the first and second contact layers are configured so that substantially no offset appear at the valence band.

2. The device according to claim 1, wherein the absorbing layer is lattice matched to at least one of the first contact layer, the barrier layer and the second contact layer.

3. The device according to any one of claims 1 and 2, wherein the first contact layer, the second contact layer and the absorbing layer comprise doped semiconductors.

4. The device according to any one of the preceding claim, wherein the barrier layer comprises undoped intrinsic semiconductor.

5. The device according to any one of the preceding claims, wherein a Sb content of the ternary alloy of InPSb is configured so as to be capable of absorbing infrared radiations of a wavelength up to 2.5 μm cut-off wavelength at room temperature.

6. The device according to claim 1, wherein the first contact layer and the absorbing layer are doped of the same conductivity type.

7. The device according to any one of the preceding claims wherein the absorbing layer is lattice matched to the barrier layer and to the first and second contact layers.

8. The device according to any one of the preceding claims, wherein the first contact layer comprises GaSb grown on a GaSb substrate.

9. The device according to any one of the preceding claims, wherein the Sb content in the ternary alloy InPSb of the absorbing layer is of about 37%.

10. The device according to any of claims 8 to 9, wherein the barrier layer comprises a ternary alloy of AlAsSb.

11. The device according to claim 10, wherein the Sb content in the ternary alloy of the AlAsSb is about 92%.

12. The device according to claim 11, wherein the second contact layer comprises GaSb.

13. A photodetector matrix comprising an array of photodetectors according to any of the preceding claims, wherein said photodetectors share a common first contact layer, a common absorption layer and a common barrier layer.

14. A night vision system for imaging an object, comprising:

- a photodetector matrix according to claim 13;
- an optical system configured for collecting light and focusing the collected light onto the photodetector matrix; and
- a spectral filter located in an optical path of light propagating toward the photodetector matrix, said spectral filter configured and operable to selectively filter out light of wavelength shorter than a predetermined value, thereby gradually shifting operation of the night vision system from mostly reflection mode to a combined reflection and thermal mode to allow the night vision system to detect light reflected from and emitted by the object being imaged.

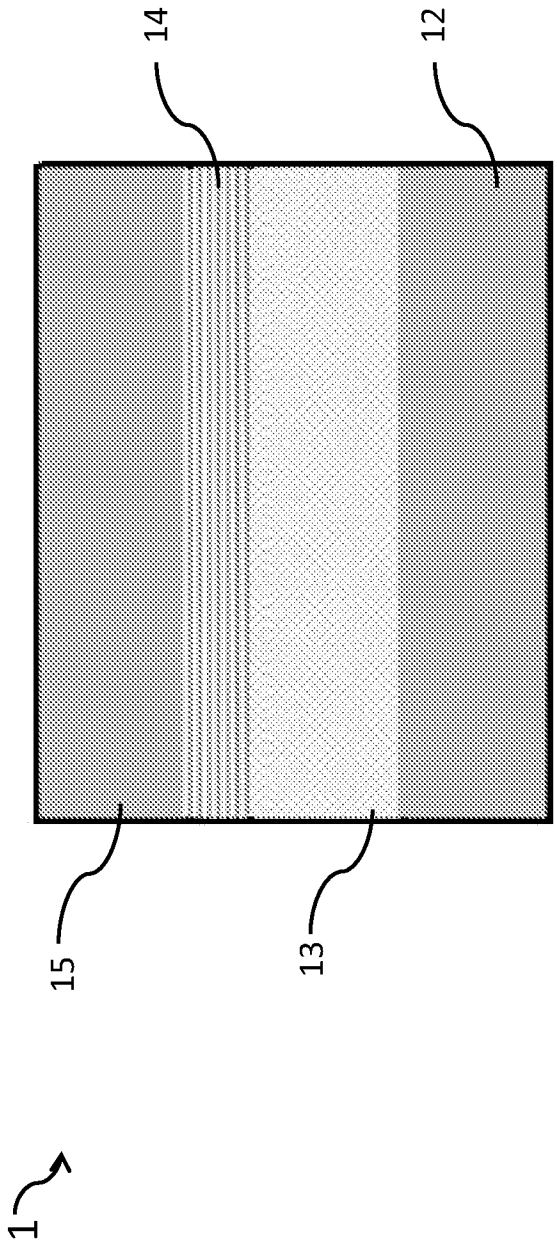


Fig. 1

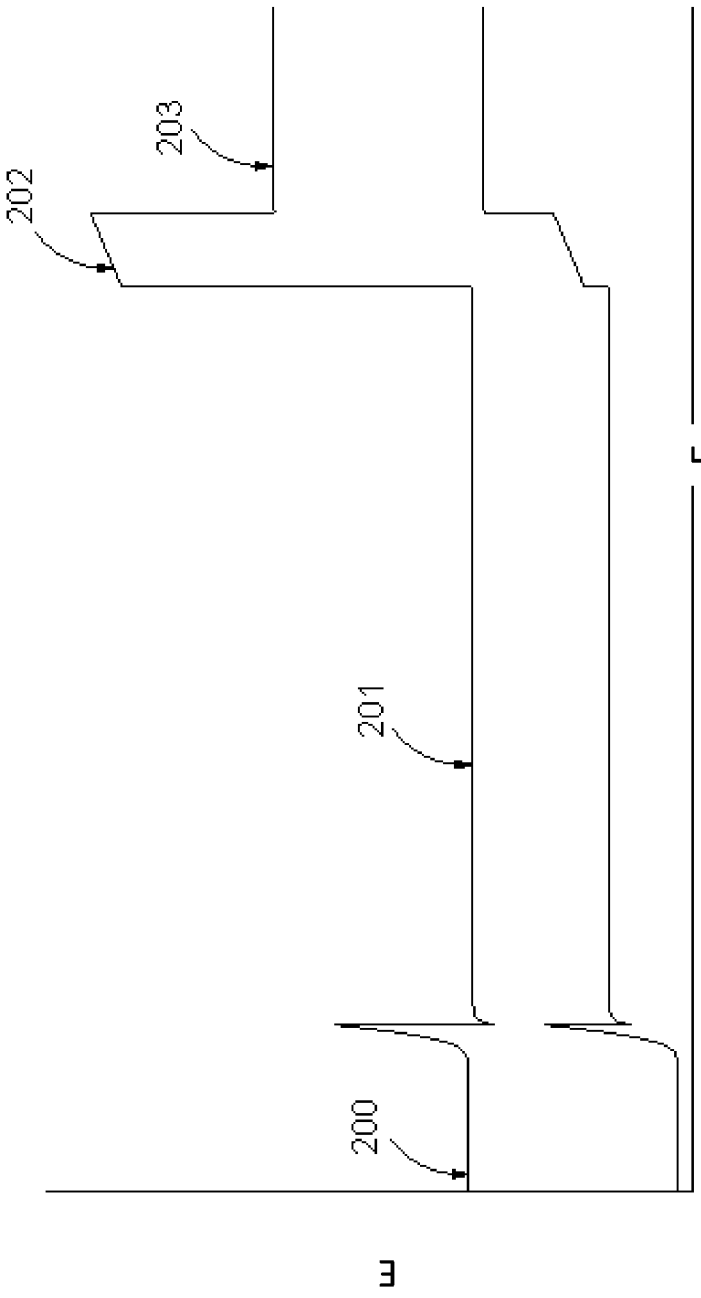


Fig. 2

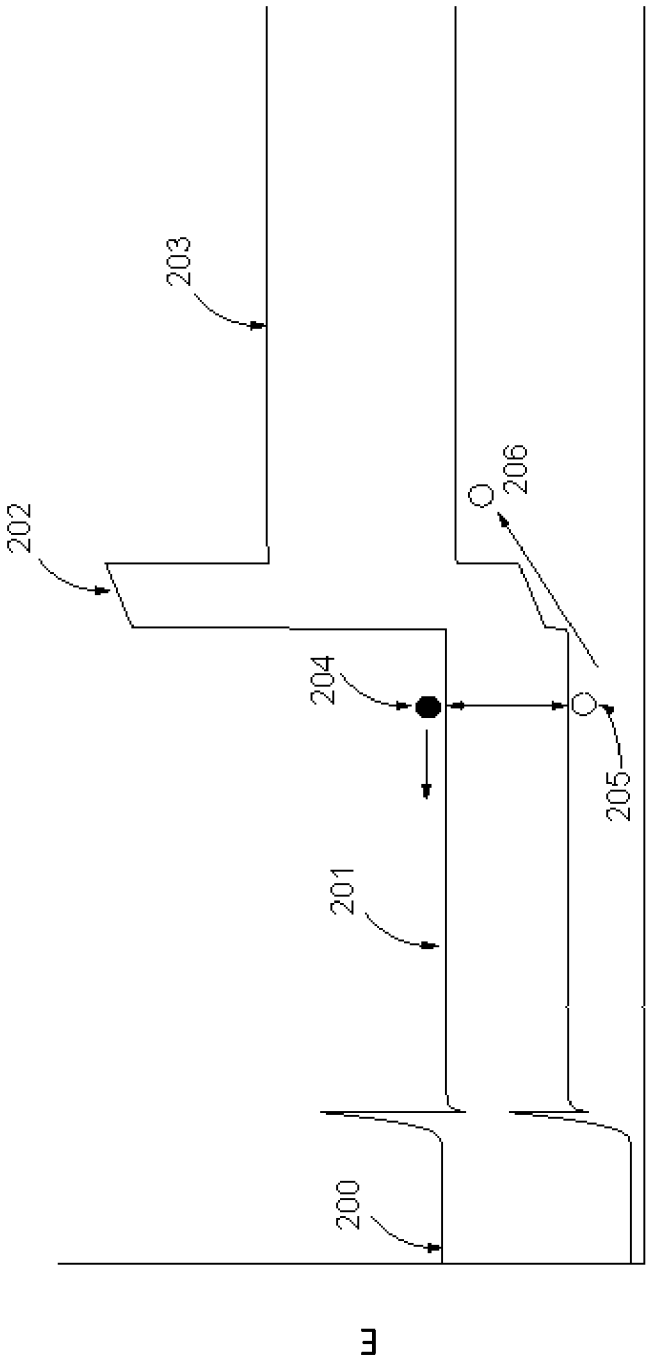


Fig. 3

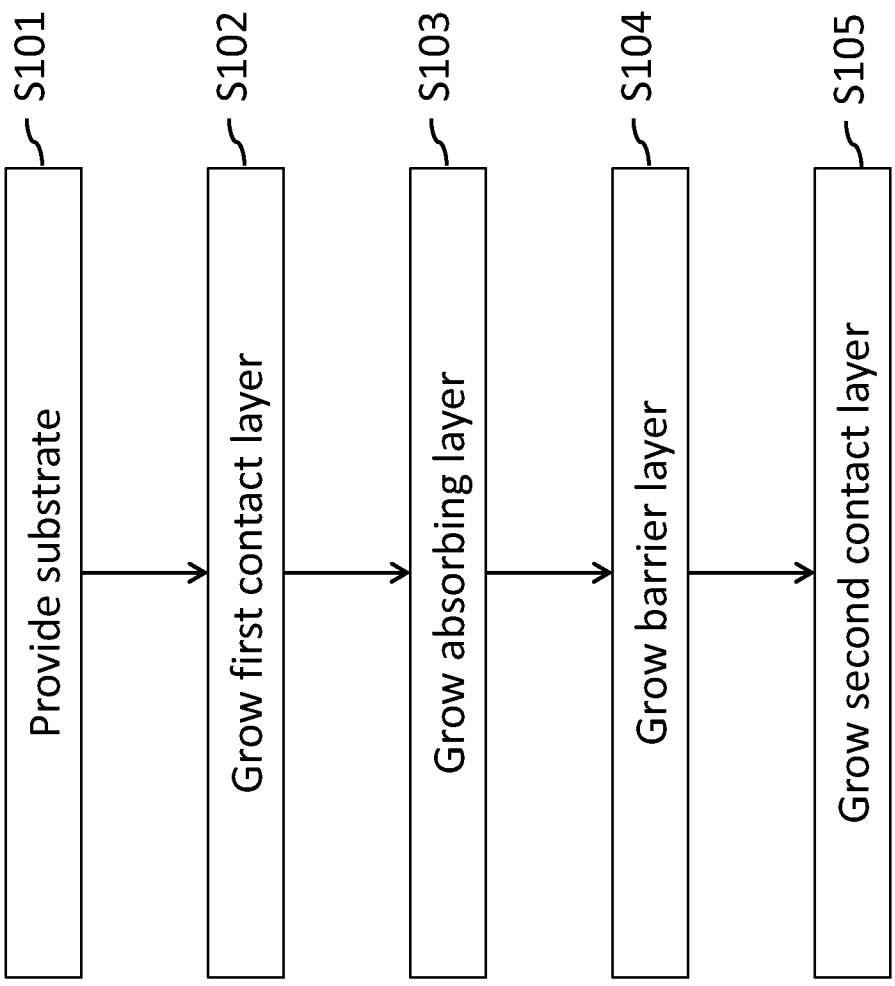

S101
Provide substrate
S102
Grow first contact layer
S103
Grow absorbing layer
S104
Grow barrier layer
S105
Grow second contact layer

Fig. 4

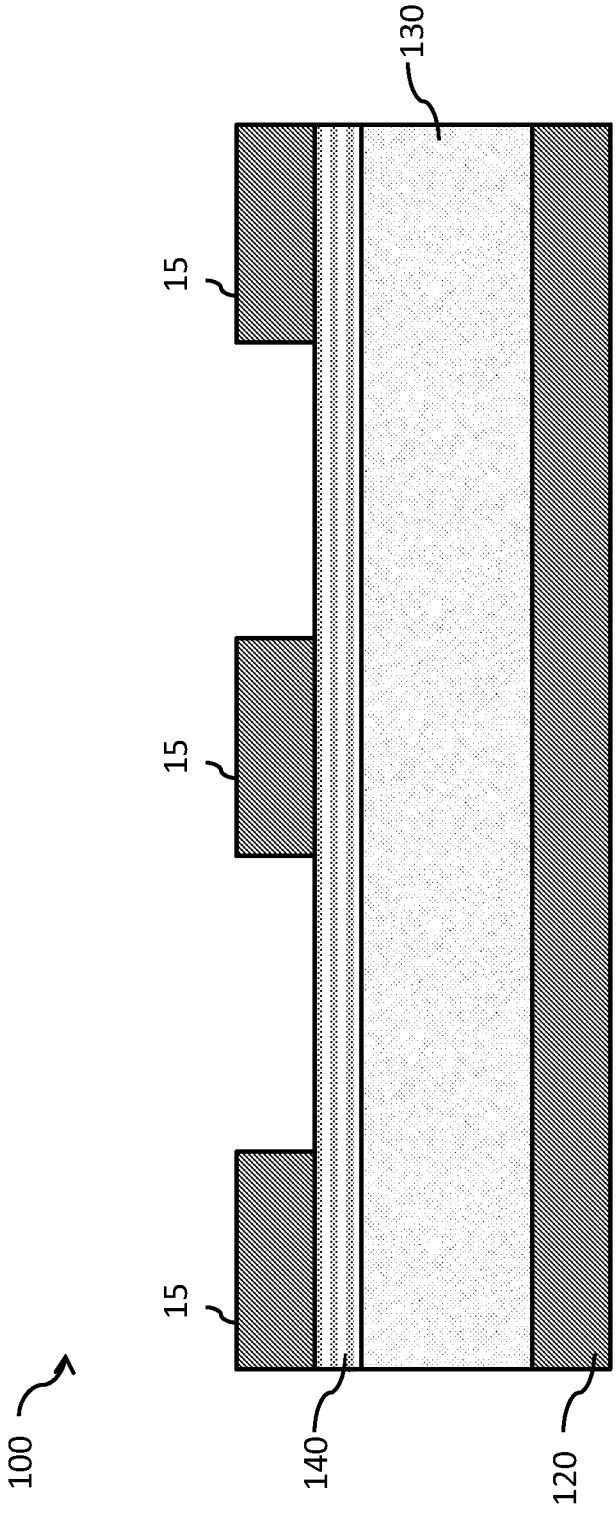


Fig. 5