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**Yanka et al.**

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(54) **OPTOELECTRONIC DETECTORS HAVING A DILUTE NITRIDE LAYER ON A SUBSTRATE WITH A LATTICE PARAMETER NEARLY MATCHING GAAS**

(58) **Field of Classification Search**  
CPC ..... H01L 31/1075; H01L 31/03046; H01L 31/03044; Y02E 10/544  
See application file for complete search history.

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(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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(Continued)

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Primary Examiner — Nikolay Yushin

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(57) **ABSTRACT**

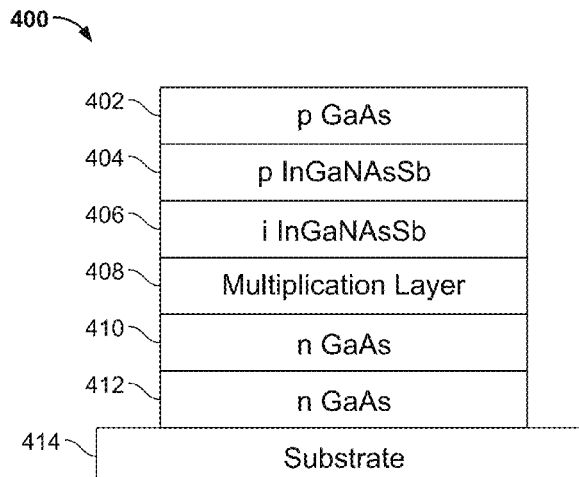
(51) **Int. Cl.**  
**H01L 31/00** (2006.01)  
**H01L 31/107** (2006.01)

(Continued)

Optoelectronic detectors having one or more dilute nitride layers on substrates with lattice parameters matching or nearly matching GaAs are described herein. A semiconductor can include a substrate with a lattice parameter matching or nearly matching GaAs and a first doped III-V layer over the substrate. The semiconductor can also include an absorber layer over the first doped III-V layer, the absorber layer having a bandgap between approximately 0.7 eV and 0.95 eV and a carrier concentration less than approximately  $1 \times 10^{16} \text{ cm}^{-3}$  at room temperature. The semiconductor can also include a second doped III-V layer over the absorber layer.

(52) **U.S. Cl.**  
CPC .... **H01L 31/1075** (2013.01); **H01L 31/03044** (2013.01); **H01L 31/03046** (2013.01); **H01L 31/03048** (2013.01); **H01L 31/105** (2013.01); **H01L 31/1848** (2013.01); **H01L 31/1852** (2013.01); **Y02E 10/544** (2013.01)

**28 Claims, 9 Drawing Sheets**



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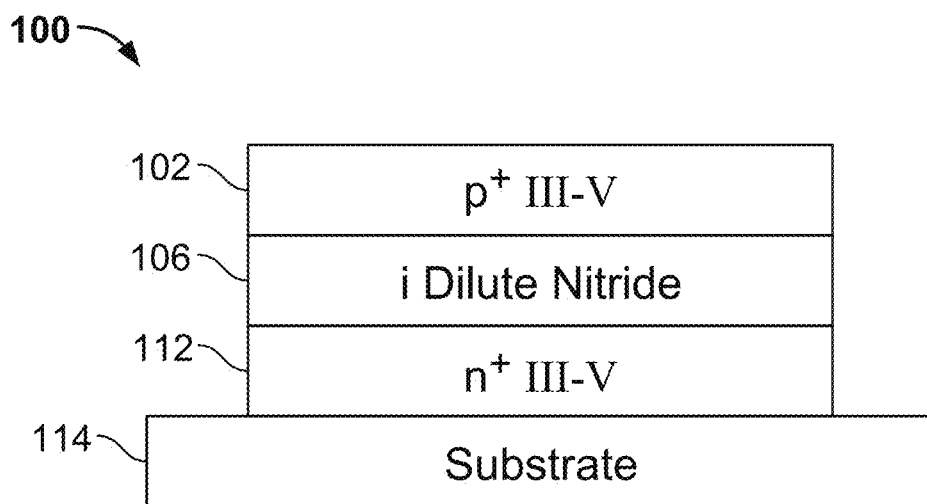


FIG. 1

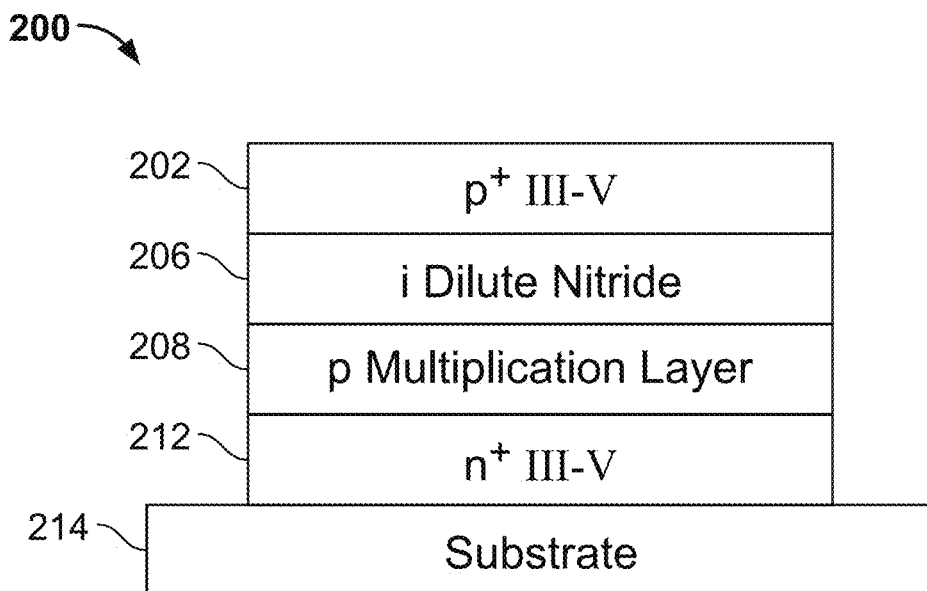


FIG. 2

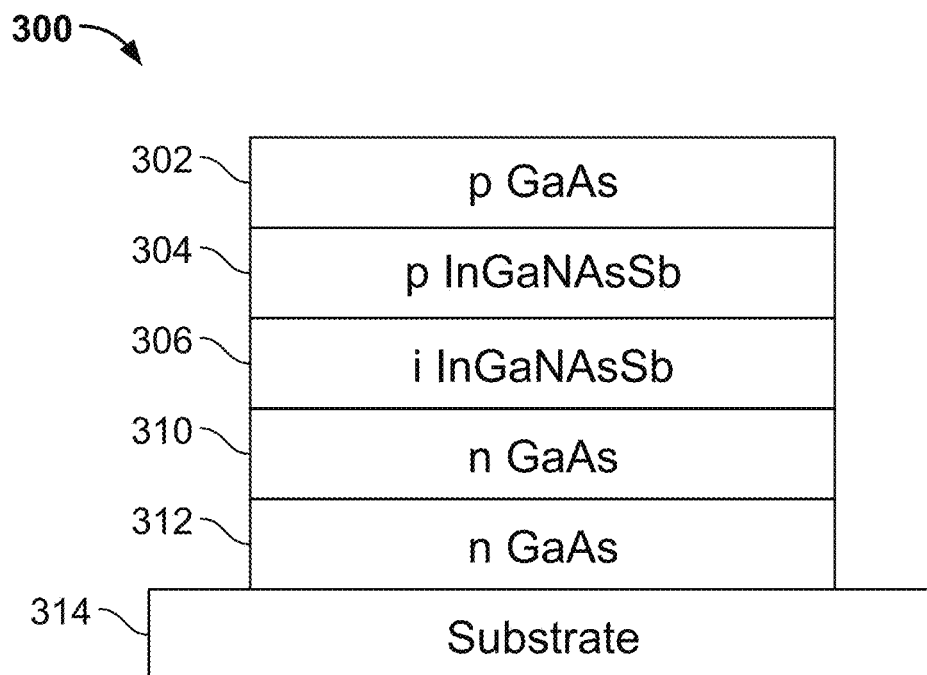


FIG. 3

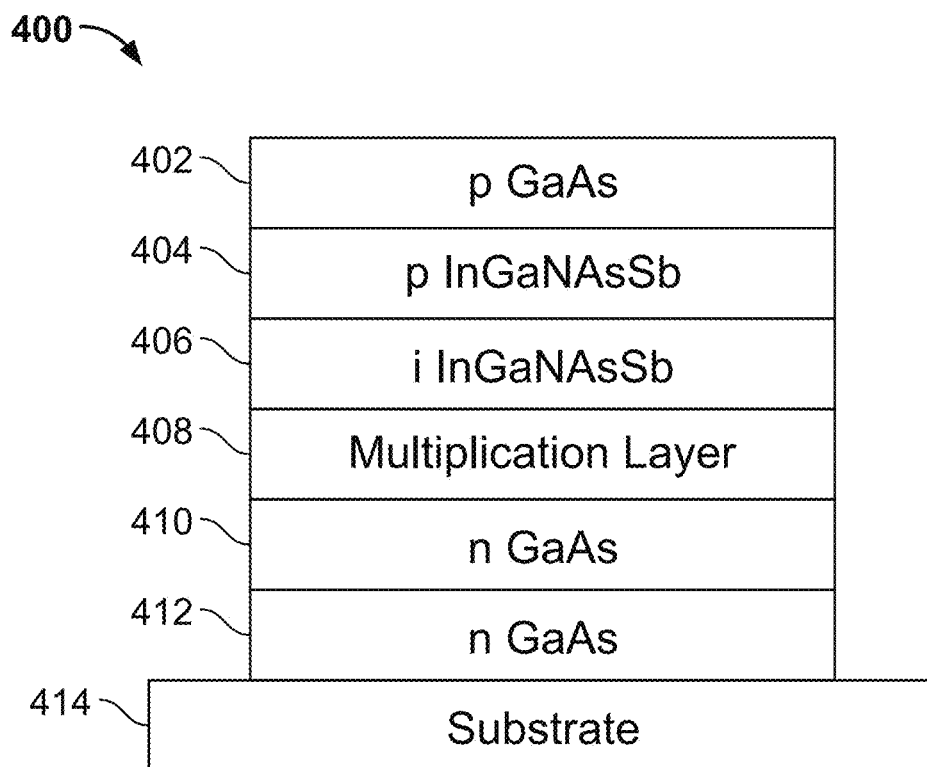


FIG. 4

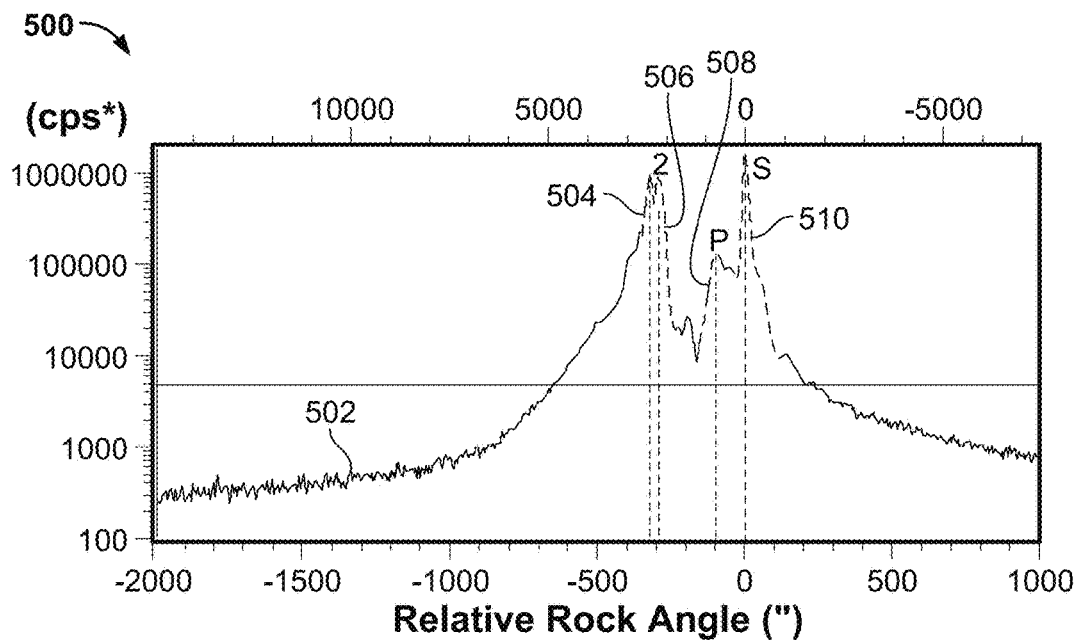


FIG. 5

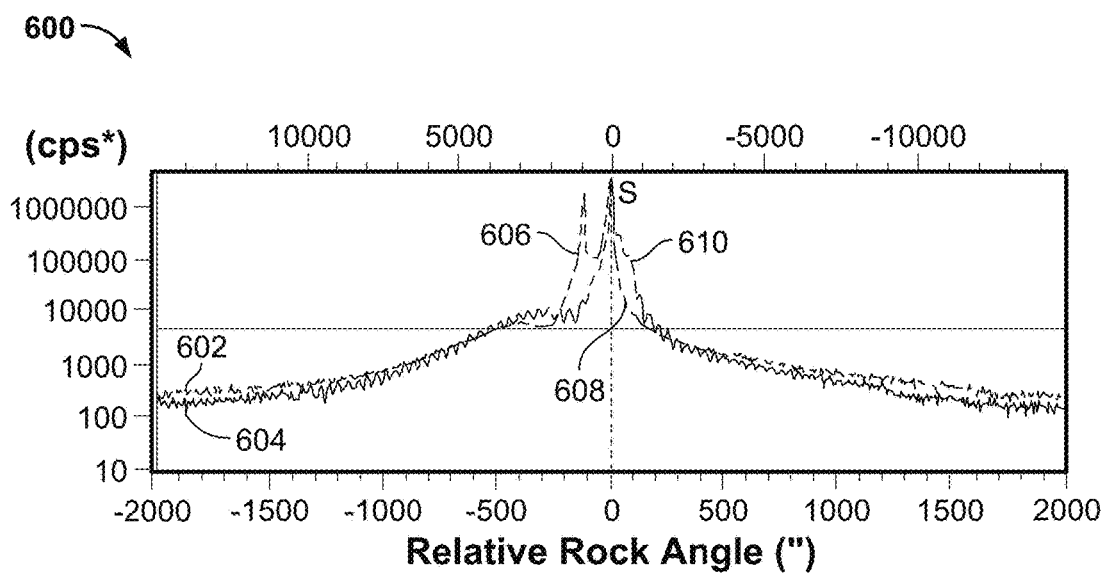


FIG. 6

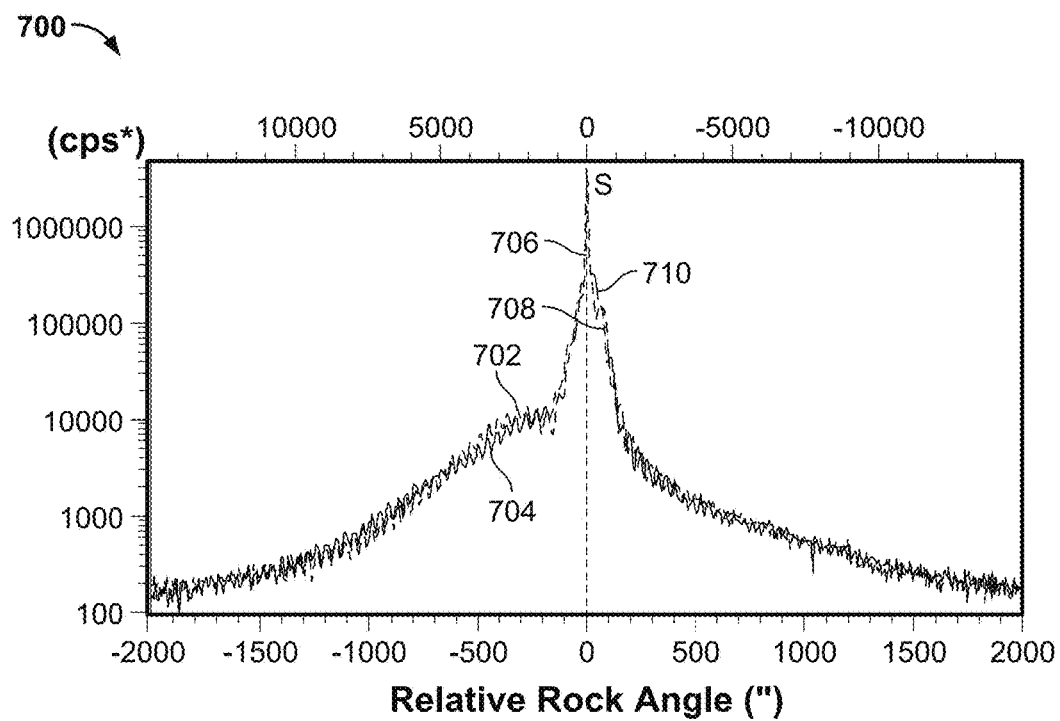


FIG. 7

800

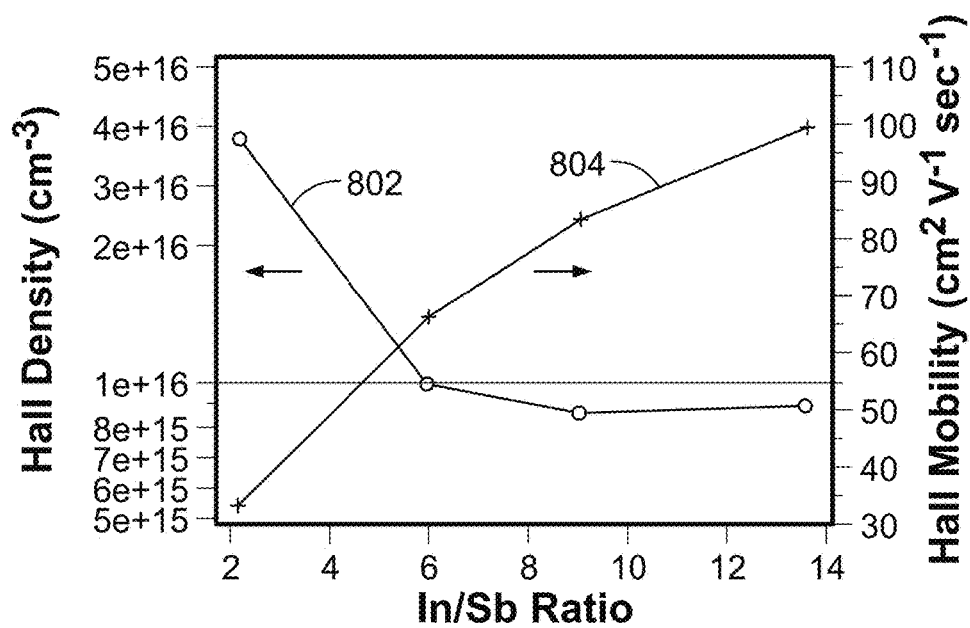


FIG. 8

900

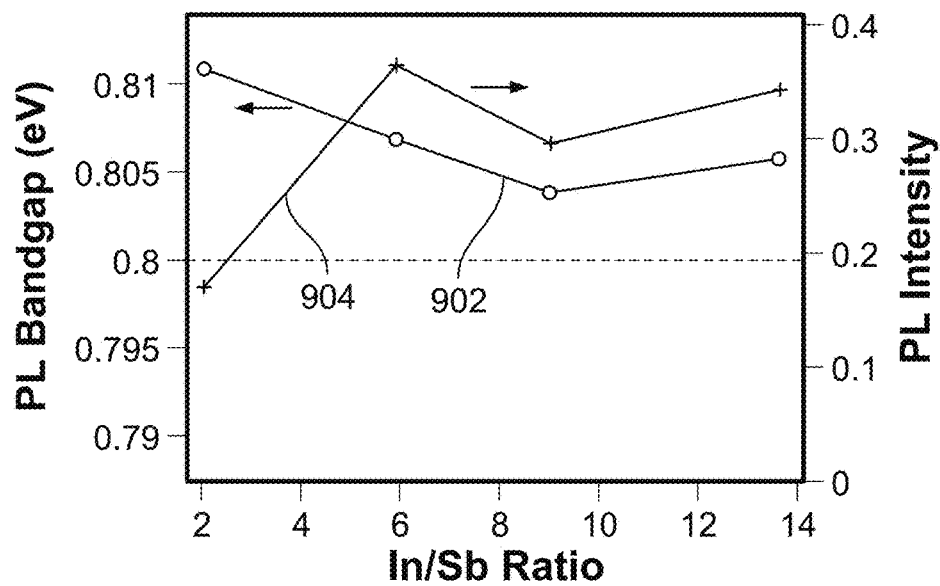


FIG. 9

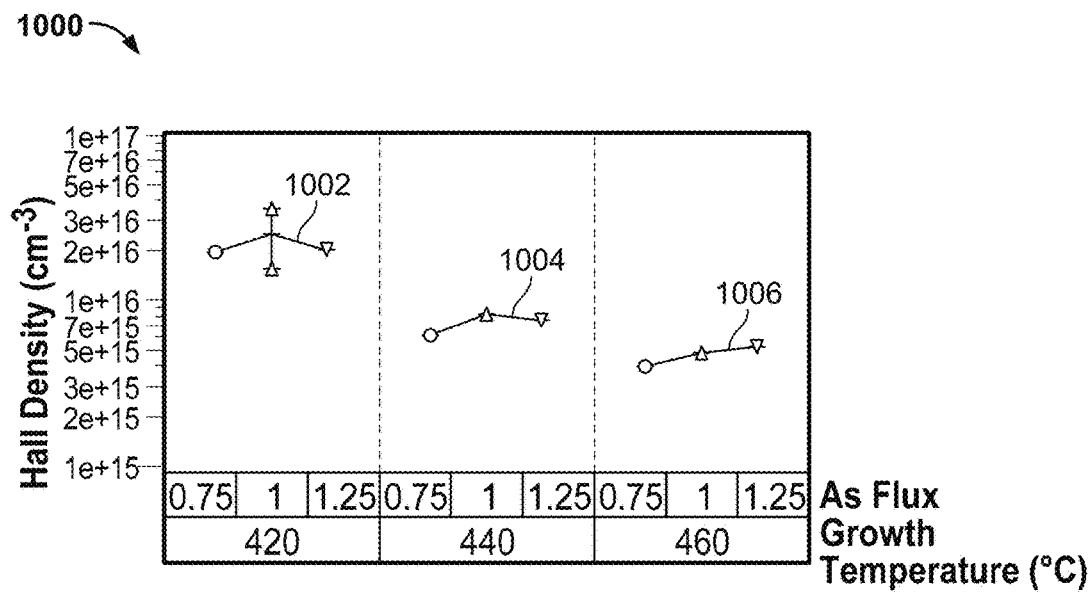


FIG. 10

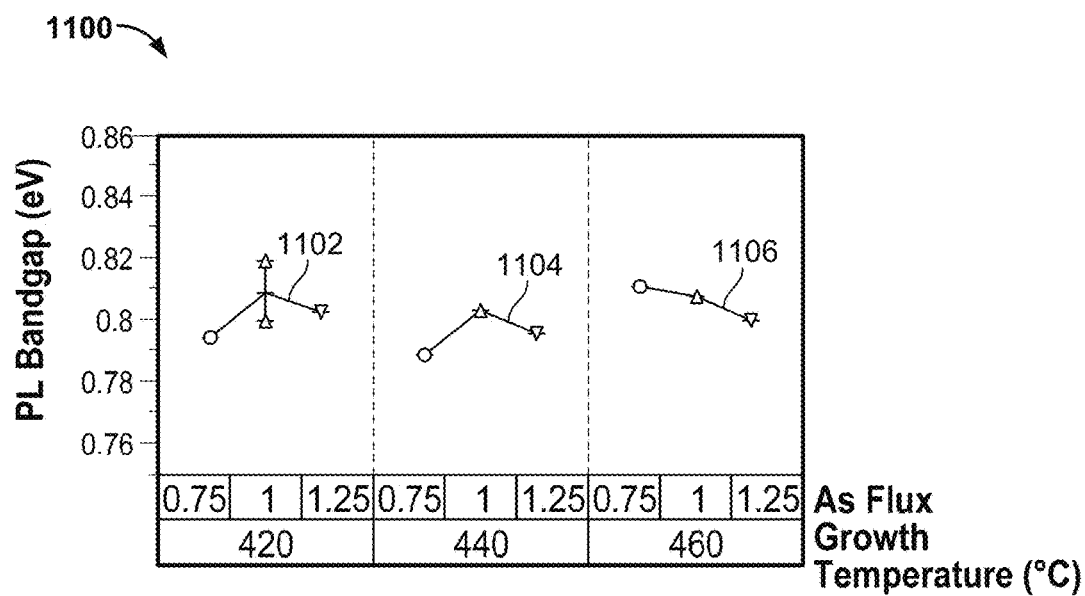


FIG. 11



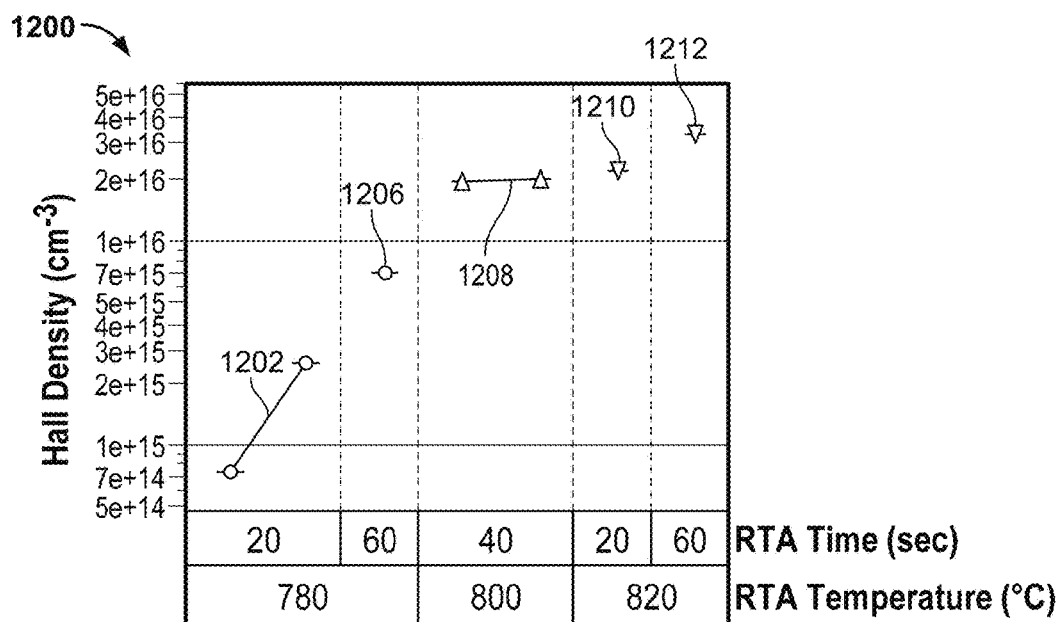


FIG. 12

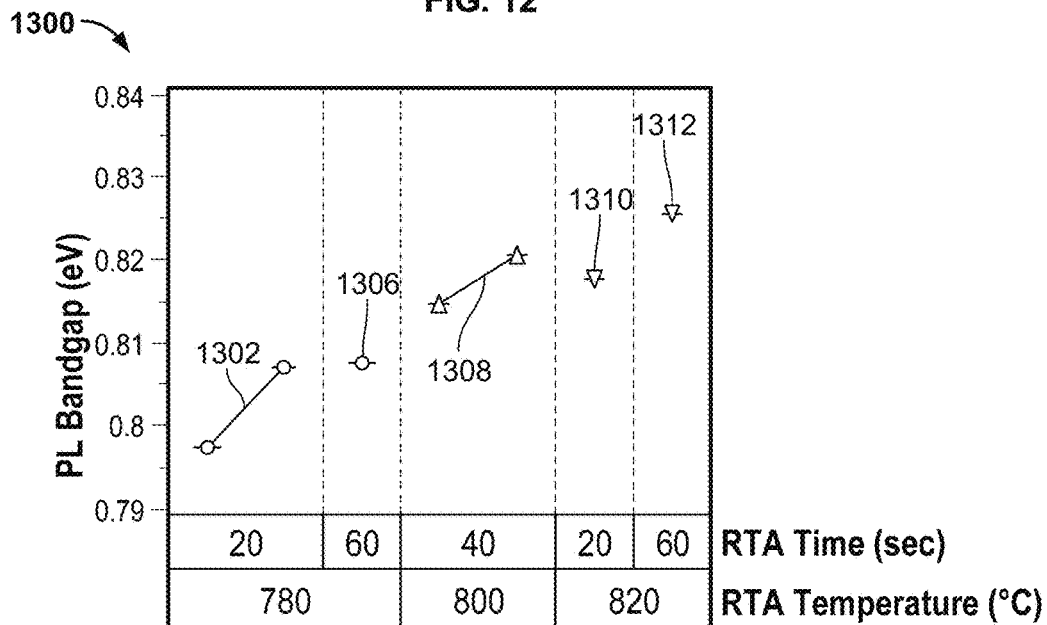


FIG. 13

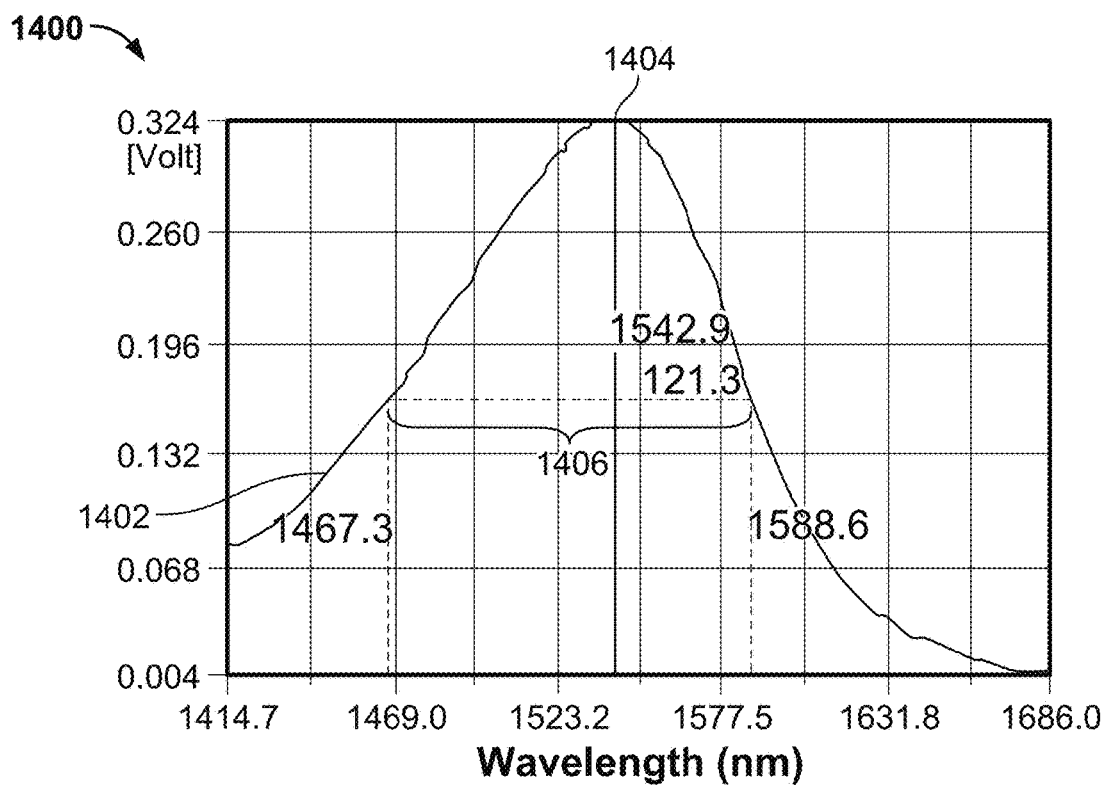


FIG. 14

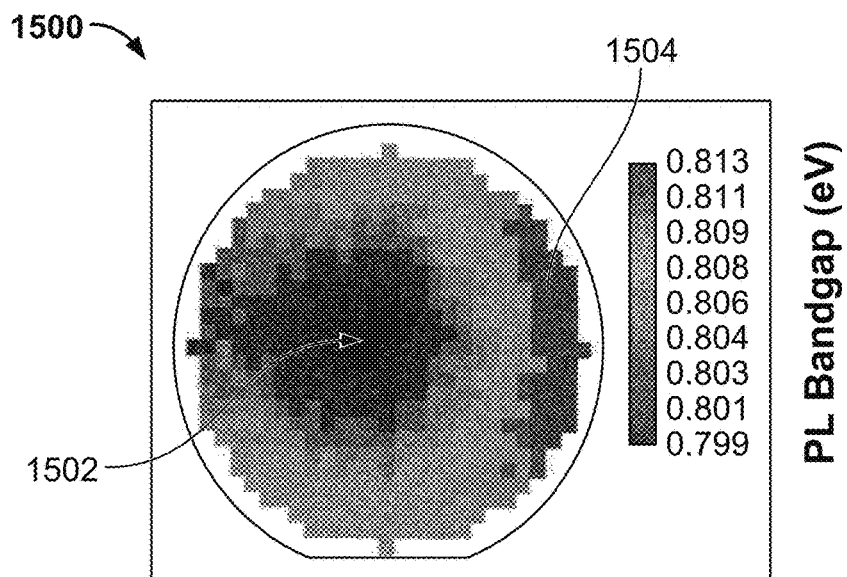


FIG. 15

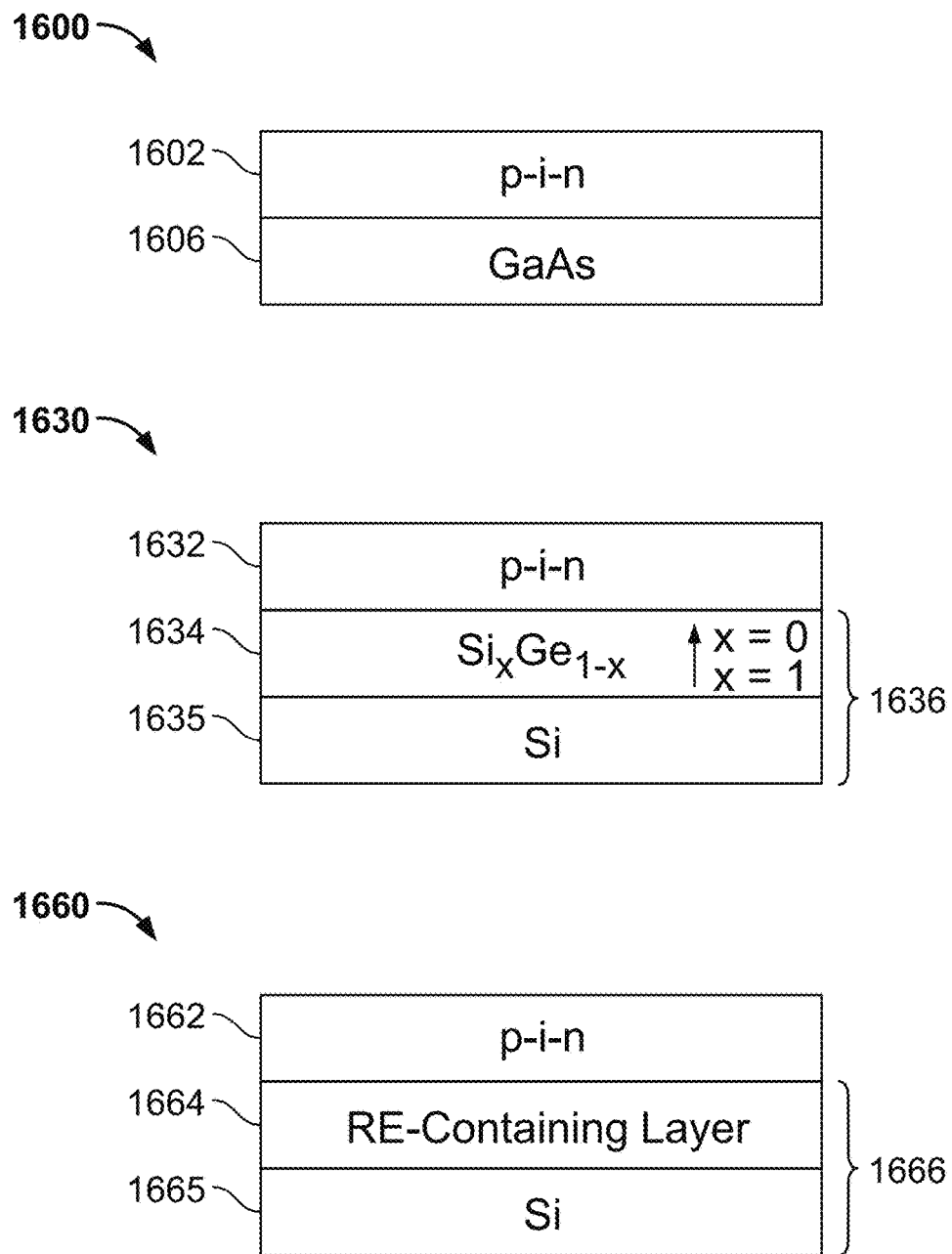


FIG. 16

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# OPTOELECTRONIC DETECTORS HAVING A DILUTE NITRIDE LAYER ON A SUBSTRATE WITH A LATTICE PARAMETER NEARLY MATCHING GAAS

## CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Application Ser. No. 62/183,060, filed Jun. 22, 2015, the entire contents of which are hereby incorporated by reference.

## BACKGROUND

III-V materials are the materials of choice for fabricating optoelectronic emitters and detectors for a variety of applications. One reason for this is that the bandgap of the material can be chosen for the specific wavelength of interest. Fiber optic systems typically use the 1.33  $\mu\text{m}$  (micrometer) and 1.50  $\mu\text{m}$  wavelengths because of their transmission characteristics.

Historically, the vast majority of 1.33  $\mu\text{m}$  and 1.50  $\mu\text{m}$  emitters and detectors employ indium gallium arsenide (InGaAs) alloys as the emitting and detecting medium. To generate high quality InGaAs needed for an emitter or detector, it is preferred that the material be as free as possible of crystalline defects. The alloy composition and thickness of the InGaAs layers needed for functional devices necessitates growth on an indium phosphide (InP) substrate since InP has the same in-plane lattice parameter as  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  ( $E_g=0.75$  eV at 300 K which corresponds to a wavelength of 1.65  $\mu\text{m}$ ).

From a cost perspective, it would be preferable to grow optoelectronic detectors and emitters on a less expensive substrate than InP, such as gallium arsenide (GaAs), germanium (Ge), or silicon (Si). However, the lattice mismatch between less expensive substrates and InGaAs alloys of desired composition results in highly defective material when grown sufficiently thick to fabricate a viable detector or emitter. Substrate cost is a significant portion of overall manufacturing cost, and therefore, finding a route to grow a material of sufficient bandgap on a less expensive substrate is of significant technical and practical interest.

## SUMMARY

Optoelectronic detectors having one or more dilute nitride layers on substrates with lattice parameters matching or nearly matching GaAs are described herein. A semiconductor can include a substrate with a lattice parameter matching or nearly matching GaAs and a first doped III-V layer over the substrate. The semiconductor can also include an absorber layer over the first doped III-V layer, the absorber layer having a bandgap between approximately 0.7 eV and 0.95 eV and a carrier concentration less than approximately  $1 \times 10^{16} \text{ cm}^{-3}$  at room temperature. The semiconductor can also include a second doped III-V layer over the absorber layer.

The absorber layer can include a dilute nitride. The dilute nitride can include  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y-z}\text{Sb}_z$ , with x, y, and z falling within the following respective ranges: ( $0 \leq x \leq 1$ ;  $0 \leq y \leq 1$ ;  $0 \leq z \leq 1$ ). In some examples, x, y, and z can fall within the following respective ranges: ( $0 \leq x \leq 0.55$ ;  $0 \leq y \leq 0.1$ ;  $0 \leq z \leq 0.1$ ).

The carrier concentration of the absorber layer can be less than approximately  $5 \times 10^{15} \text{ cm}^{-3}$ , or it can be less than approximately  $1 \times 10^{15} \text{ cm}^{-3}$ . The thickness of the absorber

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layer can be between approximately 2 micrometers and approximately 10 micrometers, or it can be between approximately 3 micrometers and approximately 5 micrometers.

The semiconductor can further include a multiplication layer between the absorber layer and one of the first and second doped III-V layers.

One or more implementations can result in a substrate with a lattice parameter matching or nearly matching GaAs. The substrate can include GaAs. The substrate can include a silicon substrate and a lattice engineered layer over the silicon substrate, with the surface of the lattice engineered layer opposite the silicon substrate having a lattice parameter that is matched or nearly matched to GaAs. The lattice engineered layer can include a  $\text{Si}_x\text{Ge}_{1-x}$  layer, with x graded from 1 at a surface of the  $\text{Si}_x\text{Ge}_{1-x}$  layer nearest the silicon substrate to 0 at a surface of the  $\text{Si}_x\text{Ge}_{1-x}$  layer opposite the silicon substrate. The lattice engineered layer can include a rare earth containing layer, with the rare earth containing layer including one or more of Sc, Y, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and/or Lu.

The first doped III-V layer can be n-type and the second doped III-V layer can be p-type. The first doped III-V layer can be p-type and the second doped III-V layer can be n-type.

## BRIEF DESCRIPTION OF THE DRAWINGS

The above and other features of the present disclosure, including its nature and its various advantages, will be more apparent upon consideration of the following detailed description, taken in conjunction with the accompanying drawings in which:

FIG. 1 depicts a semiconductor comprising a p-i-n diode, according to an illustrative implementation;

FIG. 2 depicts a semiconductor with a p-i-n diode and a multiplication layer, according to an illustrative implementation;

FIG. 3 depicts a semiconductor with a GaAs-based p-i-n diode, according to an illustrative implementation;

FIG. 4 depicts a semiconductor with a GaAs-based p-i-n diode and a multiplication layer, according to an illustrative implementation;

FIG. 5 depicts a graph that shows the characterization of the semiconductor shown in FIG. 3 by x-ray diffraction (XRD), according to an illustrative implementation;

FIG. 6 depicts a graph that shows XRD scans of intrinsic InGaAsSb layers of different thicknesses epitaxially formed on GaAs, according to an illustrative implementation;

FIG. 7 depicts a graph that shows XRD scans of InGaAsSb layers grown on p-type and semi-insulating GaAs substrates, according to an illustrative implementation;

FIG. 8 depicts a graph showing the effect of the In/Sb ratio on carrier properties of InGaAsSb, as measured by the Hall effect, according to an illustrative implementation;

FIG. 9 depicts a graph showing the effect of the In/Sb ratio on optical properties of InGaAsSb, as measured by photoluminescence (PL), according to an illustrative implementation;

FIG. 10 depicts a graph that shows the effect of growth temperature and As flux on the carrier concentration of InGaAsSb, as measured by the Hall effect, according to an illustrative implementation;

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FIG. 11 depicts a graph that shows the effect of growth temperature and arsenic flux on the bandgap of InGaNaSb, as measured by photoluminescence, according to an illustrative implementation;

FIG. 12 depicts a graph showing the effect of rapid thermal annealing (RTA) on the carrier concentration of InGaNaSb, as measured by the Hall effect, according to an illustrative implementation;

FIG. 13 includes a graph showing the effect of RTA on the bandgap of InGaNaSb as measured by photoluminescence, according to an illustrative implementation;

FIG. 14 depicts a graph that shows a photoluminescence spectrum of a 0.5  $\mu\text{m}$  layer of InGaNaSb grown on a GaAs substrate, according to an illustrative implementation;

FIG. 15 includes a colormap that shows cross-wafer variation in bandgap of a 0.5  $\mu\text{m}$  layer of InGaNaSb grown on a 150 mm GaAs substrate, according to an illustrative implementation; and

FIG. 16 illustrates several examples of p-i-n diodes formed over substrates with lattice parameters matching or nearly matching GaAs, according to an illustrative implementation.

#### DETAILED DESCRIPTION

Systems and methods described herein include processes for the growth of high quality optoelectronic detectors on a substrate with a lattice parameter matching or nearly matching GaAs. Detectors described herein use a dilute nitride layer, typically an  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y-z}\text{Sb}_z$  layer as the absorbing medium, where x ranges from 0 to 0.55, y ranges from 0 to 0.1, and z ranges from 0 to 0.1, herein referred to as the InGaNaSb layer. The dilute nitride is a III-V material that includes low concentrations of nitrogen, concentrations that are low alloy-level concentrations and are higher than doping-level concentrations. The dilute nitride layer may have trace amounts of dopants or contamination, but in amounts that do not prevent the layer from functioning in a detector. In some examples the optoelectronic detectors use a p-i-n structure. In a typical p-i-n, the absorption medium is an intrinsic semiconductor (i) is sandwiched between an n-type semiconductor and a p-type semiconductor. The n-type region has electrons as the majority carrier, usually due to doping by donor dopants. The p-type region has holes as the majority carrier, usually due to doping by acceptor dopants. In operation, the diode is reverse biased which serves to “sweep” out carriers generated by photons of sufficient energy.

The substrate with a lattice parameter matching or nearly matching GaAs may comprise a GaAs substrate, a Ge substrate, or a lattice engineered substrate. Examples of lattice engineered substrates include a substrate comprising a graded SiGe layer on a Si handle wafer and a substrate comprising a rare-earth containing layer on a Si handle wafer. The lattice parameter is a dimension of a unit cell in a crystal lattice. The substrate with a lattice parameter matching or nearly matching GaAs may have a lattice parameter that is the same as or slightly different than the lattice parameter of GaAs (5.65 Å), but is similar enough that high-quality GaAs can be epitaxially grown on the substrate surface. High quality GaAs can include a defect level that is comparable to or lower than a defect level of an  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  layer grown on an InP substrate. This can mean the substrate has a lattice parameter different than that of GaAs by less than or equal to 3%, less than 1%, or less than 0.5%.

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An InGaNaSb absorber layer of high quality enables low cost, high performance detectors. One reason for this is that the absorber layer can be grown coherently (i.e., crystalline, non-relaxed and with minimal defectivity) on a substrate with a lattice parameter matching or nearly matching GaAs. The composition of the InGaNaSb layer can be tuned so that a layer of desired bandgap and thickness can be coherently grown on a substrate with a lattice parameter matching or nearly matching GaAs with minimal defects. The bandgap is the energy difference between conduction and valence bands of a material, and can be direct (where electronic transitions between the bands can occur with only emission or absorption of a photon) or indirect (where electronic transitions between the bands require emission or absorption of a phonon in addition to emission or absorption of a photon). III-V materials generally have direct bandgaps, but the layers described herein can have direct or indirect bandgaps.

FIG. 1 depicts a semiconductor 100 comprising a p-i-n diode. The semiconductor 100 includes a substrate 114, an  $\text{n}^+$  III-V layer 112 epitaxially formed over the substrate 114, an intrinsic dilute nitride layer 106 epitaxially formed over the  $\text{n}^+$  III-V layer 112, and a  $\text{p}^+$  III-V layer 102 epitaxially formed over the dilute nitride layer 106.

The III-V layers 102 and 112 can include any III-V material, such as GaAs, InGaAs, AlGaAs, InGaP, InGaAsP, InGaAsN, InGaNaSb, or another III-V material. The substrate 114 can be a semiconducting, conducting, or an insulating substrate. The upper surface of the substrate 114 has a lattice parameter that matches or nearly matches GaAs. Examples of the substrate 114 are described below with reference to FIG. 16. The dilute nitride layer 106 is an intrinsic layer in the p-i-n diode and serves as an absorption medium. The terms absorber layer and absorption medium can be used to describe any layer that absorbs photons.

The dilute nitride layer 106 has a lattice parameter that is compatible with the III-V layers 102 and 112. The dilute nitride layer 106 can be lattice-matched to the III-V layers 102 and 112, or it may have a lattice parameter that is relatively close (nearly matched) to the III-V layers 102 and 112. Thus, the dilute nitride layer 106 has a sufficiently low defect level such that it has good optical performance. Such a sufficiently low defect level can include a comparable or lower defect level than would occur in an  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  layer grown on an InP substrate. Each of the layers 102, 106, and 112 and the substrate 114 can include one or more layers that improve lattice-matching, interface quality, electron transport, hole transport and/or other optoelectronic properties.

FIG. 2 depicts a semiconductor 200 with a p-i-n diode and a multiplication layer. The semiconductor 200 is similar to the semiconductor 100, but also includes a multiplication layer to amplify the photocurrent generated by the intrinsic layer of the p-i-n diode. The structure of the semiconductor 200 can be described as an avalanche photodiode (APD) structure. In an APD, the addition of the multiplication layer results in an additional p-i-n or p-n junction. This allows a higher reverse bias to be applied, resulting in carrier multiplication via the avalanche process. As a result the gain (number of electrons per photon) of the device (as compared to a standard p-i-n) is increased. This results in a higher sensitivity device. The semiconductor 200 includes a substrate 214, an  $\text{n}^+$  III-V layer 212 epitaxially formed over the substrate 214, a p-type multiplication layer 208 formed over the  $\text{n}^+$  III-V layer 212, an intrinsic dilute nitride layer 206

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epitaxially formed over the p-type multiplication layer **208**, and a p<sup>+</sup> III-V layer **202** epitaxially formed over the dilute nitride layer **206**.

The III-V layers **202** and **212** can include any III-V material, such as GaAs, InGaAs, AlGaAs, InGaP, InGaAsP, InGaAsN, InGaAsSb, or another III-V material. The substrate **214** can be a semiconducting, conducting, or an insulating substrate. The upper surface of the substrate **214** has a lattice parameter that matches or nearly matches GaAs. Examples of the substrate **214** are described below with reference to FIG. 16. The dilute nitride layer **206** is an intrinsic layer in the p-i-n diode and serves as an optical absorber layer.

The dilute nitride layer **206** has a lattice parameter that is compatible with the III-V layers **202** and **212**. The dilute nitride layer **206** can be lattice-matched to the III-V layers **202** and **212**, or it may have a lattice parameter that is relatively close (nearly matched) to the III-V layers **202** and **212**. Thus, the dilute nitride layer **206** has a sufficiently low defect level such that it has good optical performance. Such a sufficiently low defect level can include a comparable or lower defect level than would occur in an In<sub>0.53</sub>Ga<sub>0.47</sub>As layer grown on an InP substrate. Each of the layers **202**, **206**, and **212** and the substrate **214** can include one or more layers that improve lattice-matching, interface quality, electron transport, hole transport and/or other optoelectronic properties.

The multiplication layer **208** can be a p-type III-V layer that amplifies the current generated by the dilute nitride layer **206** through avalanche multiplication. Thus, for each free carrier (electron or hole) generated by the dilute nitride layer **206**, the multiplication layer **208** generates one or more carriers via the avalanche effect. Thus, the multiplication layer **208** increases the total current generated by the semiconductor **200**.

FIG. 3 depicts a semiconductor **300** with a GaAs-based p-i-n diode. The semiconductor **300** includes a substrate **314** with a top surface having a lattice parameter matching or nearly matching that of GaAs. The substrate **300** includes an n-type GaAs layer **312** epitaxially formed over the substrate **314**, and an n-type GaAs layer **310** epitaxially formed over the GaAs layer **312**. The GaAs layer **312** can be more heavily doped than the GaAs layer **310**. The semiconductor **300** also includes an intrinsic InGaAsSb layer **306** epitaxially formed over the GaAs layer **310**, a p-type InGaAsSb layer **304** epitaxially formed over the intrinsic InGaAsSb layer **306**, and a p-type GaAs layer **302** epitaxially formed over the p-type InGaAsSb layer **304**. The p-type GaAs layer **302** can be more heavily doped than the p-type InGaAsSb layer **304**. The InGaAsSb layer **304** and the InGaAsSb layer **306** can each have the composition In<sub>x</sub>Ga<sub>1-x</sub>N<sub>y</sub>As<sub>1-y-z</sub>Sb<sub>z</sub> (0 ≤ x ≤ 1; 0 ≤ y ≤ 1; 0 ≤ z ≤ 1). The mole fractions x, y, and z can have different values in the different layers **302** and **304**. In some examples, x ranges from 0 to 0.55, y ranges from 0 to 0.1, and z ranges from 0 to 0.1.

In some examples, the p-type GaAs layer **302** can have a thickness of approximately 0.2 μm and can be doped with Be or C to result in a free hole concentration of approximately 1.5 × 10<sup>19</sup> cm<sup>-3</sup>. The p-type InGaAsSb layer **304** can have a thickness of approximately 0.25 μm and can be doped with Be or C to result in a free hole concentration of approximately 7 × 10<sup>18</sup> cm<sup>-3</sup>. The composition of the InGaAsSb layer **304** can be selected to result in a bandgap of approximately 0.8 eV. The InGaAsSb layer **306** can have a thickness of approximately 3 μm and can be unintentionally doped (UID) with a free carrier concentration of approximately 6 × 10<sup>14</sup> cm<sup>-3</sup>. The carrier concentration of a material

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is the number density of charge carriers such as electrons or holes in the material. The carrier concentration of a material is sometimes expressed in units of electrons-cm<sup>-3</sup>, holes-cm<sup>-3</sup>, or atoms-cm<sup>-3</sup> (referring to the atomic dopant density), but more often, the name of the particle is omitted while referencing the same quantity and the carrier concentration is simply expressed in units of cm<sup>-3</sup>. UID semiconductors do not have dopants that were intentionally added, but can include a nonzero concentration of impurities that act as dopants. The InGaAsSb layer **306** can act as an absorber layer to absorb incident photons. The InGaAsSb layer **306** can have primarily holes as the free carriers, making the layer **306** p-type. The composition of the InGaAsSb layer **306** can also be selected to result in a bandgap of approximately 0.8 eV. The InGaAsSb layer **306** can have a bandgap between approximately 0.8 eV and approximately 0.95 eV, corresponding to wavelengths between 1.3 μm and 1.55 μm.

With the appropriate concentration of In, InGaAs alloys can have bandgaps within the wavelength range 1.3-1.55 μm. However, the lattice parameters of such InGaAs alloys are similar to that of InP, but not that of GaAs or Si. Thus, InGaAs absorbers are not readily compatible with epitaxial growth on GaAs or silicon substrates. However, the addition of N to InGaAs can reduce the bandgap while resulting in a lattice parameter that matches or nearly matches GaAs. Addition of Sb to InGaAs results in improved crystallinity and lower background carrier concentration for a given bandgap. Sb can mitigate some defect types or can act as a surfactant to enhance device performance. Sb can improve the incorporation of N, allowing a lower N flux or flow to be used to grow a material of a given N concentration and correspondingly bandgap, thus reducing the background carrier concentration. Accordingly, the bandgap of InGaAsSb can be tailored to the appropriate range while maintaining good crystallinity and lattice matching to GaAs.

The GaAs layer **310** can have a thickness of approximately 0.5 μm and can be doped with silicon to result in an n-type material with a free carrier concentration of approximately 2 × 10<sup>15</sup> cm<sup>-3</sup>. The GaAs layer **312** can have a thickness of approximately 2.5 μm and can be doped with silicon to result in an n-type material with a free carrier concentration of approximately 5 × 10<sup>18</sup> cm<sup>-3</sup>. The substrate **314** can include one or more layers, and the top surface of the substrate can have a lattice parameter matching or nearly matching GaAs. This results in a high quality interface between the GaAs layer **312** and the substrate **314**, and reduces defect levels in the semiconductor **300**. Some examples of the substrate **314** are described below with reference to FIG. 16. Accordingly, the semiconductor **300** includes a GaAs-based p-i-n diode that is optically active in the 1.3-1.55 μm range and is formed on the top surface of a substrate with a lattice parameter matching or nearly matching that of GaAs.

FIG. 4 depicts a semiconductor **400** with a GaAs-based p-i-n diode and a multiplication layer. The semiconductor **400** is similar to the semiconductor **300**, but also includes an avalanche multiplication layer to amplify the photocurrent generated by the intrinsic layer of the p-i-n diode. The semiconductor **400** includes a substrate **414** with a top surface having a lattice parameter matching or nearly matching that of GaAs. The substrate **400** includes an n-type GaAs layer **412** epitaxially formed over the substrate **414**, and an n-type GaAs layer **410** epitaxially formed over the n-type GaAs layer **412**. The GaAs layer **412** can be more heavily doped than the GaAs layer **410**. The semiconductor **400** also includes a multiplication layer **408** epitaxially formed over

the GaAs layer **410**, an intrinsic InGaAsSb layer **406** epitaxially formed over the multiplication layer **408**, a p-type InGaAsSb layer **404** epitaxially formed over the intrinsic InGaAsSb layer **406**, and a p-type GaAs layer **402** epitaxially formed over the p-type InGaAsSb layer **404**. The p-type GaAs layer **402** can be more heavily doped than the p-type InGaAsSb layer **404**. The InGaAsSb layer **404** and the InGaAsSb layer **406** can each have the composition  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y-z}\text{Sb}_z$  ( $0 \leq x \leq 1$ ;  $0 \leq y \leq 1$ ;  $0 \leq z \leq 1$ ). The mole fractions  $x$ ,  $y$ , and  $z$  can have different values in the different layers **402** and **404**. In some examples,  $x$  ranges approximately from 0 to 0.55, inclusive,  $y$  ranges approximately from 0 to 0.1, inclusive, and  $z$  ranges approximately from 0 to 0.1, inclusive.

In some examples, the p-type GaAs layer **402** can have a thickness of approximately 0.2  $\mu\text{m}$  and can be doped with Be or C to result in a free hole concentration of approximately  $1.5 \times 10^{19} \text{ cm}^{-3}$ . The p-type InGaAsSb layer **404** can have a thickness of approximately 0.25  $\mu\text{m}$  and can be doped with Be or C to result in a free hole concentration of approximately  $7 \times 10^{18} \text{ cm}^{-3}$ . The composition of the InGaAsSb layer **404** can be selected to result in a bandgap of approximately 0.8 eV. The InGaAsSb layer **406** can have a thickness of approximately 3  $\mu\text{m}$  and can be unintentionally doped (UID) with a free carrier concentration of approximately  $6 \times 10^{14} \text{ cm}^{-3}$ . The InGaAsSb layer **406** can act as an absorber layer to absorb incident photons. The InGaAsSb layer **406** can have primarily holes as the free carriers, making the layer **406** p-type. The composition of the InGaAsSb layer **406** can also be selected to result in a bandgap of approximately 0.8 eV. The InGaAsSb layer **406** can have a bandgap between approximately 0.8 eV and approximately 0.95 eV, corresponding to wavelengths between 1.3  $\mu\text{m}$  and 1.55  $\mu\text{m}$ .

With the appropriate concentration of In, InGaAs alloys can have bandgaps within the wavelength range 1.3-1.55  $\mu\text{m}$ . However, the lattice parameters of such InGaAs alloys are similar to that of InP, but not that of GaAs or Si. Thus, InGaAs absorbers are not readily compatible with epitaxial growth on GaAs or silicon substrates. However, the addition of N to InGaAs can reduce the bandgap while resulting in a lattice parameter that matches or nearly matches GaAs. Addition of Sb to InGaAs results in improved crystallinity and lower background carrier concentration for a given bandgap. Sb can mitigate some defect types or can act as a surfactant to enhance device performance. Sb can improve the incorporation of N, allowing a lower N flux or flow to be used to grow a material of a given N concentration and correspondingly bandgap, thus reducing the background carrier concentration. Accordingly, the bandgap of InGaAsSb can be tailored to the appropriate range while maintaining good crystallinity and lattice matching to GaAs.

The GaAs layer **410** can have a thickness of approximately 0.5  $\mu\text{m}$  and can be doped with silicon to result in an n-type material with a free carrier concentration of approximately  $2 \times 10^{15} \text{ cm}^{-3}$ . The GaAs layer **412** can have a thickness of approximately 2.5  $\mu\text{m}$  and can be doped with silicon to result in an n-type material with a free carrier concentration of approximately  $5 \times 10^{18} \text{ cm}^{-3}$ . The substrate **414** can include one or more layers, and the top surface of the substrate can have a lattice parameter matching or nearly matching GaAs. This results in a high quality interface between the GaAs layer **412** and the substrate **414**, and reduces defect levels in the semiconductor **400**. Some examples of the substrate **414** are described below with reference to FIG. 16. Accordingly, the semiconductor **400** includes a GaAs-based p-i-n diode that is optically active in

the 1.3-1.55  $\mu\text{m}$  range and is formed on the top surface of a substrate with a lattice parameter matching or nearly matching that of GaAs.

The multiplication layer **408** can be a p-type III-V layer that amplifies the current generated by the dilute nitride layer **406** through avalanche multiplication. One example of a p-type III-V layer is a p-type GaAs layer. For each free carrier (electron or hole) generated by the dilute nitride layer **406**, the multiplication layer **408** generates one or more carriers via the avalanche effect. Thus, the multiplication layer **408** increases the total current generated by the semiconductor **400**.

In some examples, the bandgap of one or more of the layers **106**, **206**, **304**, **306**, **404**, and **406** is between 0.7 eV and 0.95 eV. In some examples, the bandgap of one or more of the layers **106**, **206**, **304**, **306**, **404**, and **406** is 0.7 eV, 0.75 eV, 0.80 eV, 0.85 eV, 0.90 eV, or 0.95 eV. In some examples, one or more of the layers **106**, **206**, **304**, **306**, **404**, and **406** is up to 10  $\mu\text{m}$  thick. In some examples, one or more of the layers **106**, **206**, **304**, **306**, **404**, and **406** is 0.001-1, 0.05-5, 0.5-5, 0.1-1, 1-10, 0.001-0.005, 0.005-0.01, 0.01-0.05, 0.05-0.1, 0.1-0.5, 0.5-1, 1-2, 2-3, 3-4, 4-5, 5-6, 6-7, 7-8, 8-9, 9-10, 2-10, 3-10, or 3-5  $\mu\text{m}$  (micrometers) thick. The layers **106**, **206**, **306**, and **406** have a free carrier concentration caused by unintentional dopants. The carrier concentration at room temperature of one or more of the layers **106**, **206**, **306**, and **406** can be below approximately  $1 \times 10^{16} \text{ cm}^{-3}$ , can be below approximately  $5 \times 10^{15} \text{ cm}^{-3}$ , can be below approximately  $1 \times 10^{15} \text{ cm}^{-3}$ , and can be between approximately  $1 \times 10^{13} \text{ cm}^{-3}$  and  $5 \times 10^{15} \text{ cm}^{-3}$ . Room temperature can include a range of temperatures that the layers **106**, **206**, **306**, and **406** will experience during normal operation, such as approximately 20° C., between 15° C. and 25° C., between 0° C. and 30° C., and between -20° C. and 50° C. Because the layers **106**, **206**, **306**, and **406** are unintentionally doped, carrier freeze-out will occur at higher temperatures than for semiconductors with higher doping levels. Because of this freeze-out effect, a sample measured at a reduced or cryogenic temperature will exhibit a lower carrier concentration than the same sample measured at room temperature. Thus, measuring carrier concentrations at room temperature provides an accurate indication of carrier concentrations to be expected during device operation, as opposed to measuring carrier concentrations at reduced or cryogenic temperatures.

One or more of the layers **106**, **206**, **304**, **306**, **404**, and **406** can have In molar concentrations between approximately 10% and approximately 20%, N molar concentrations between approximately 3% and approximately 7%, and Sb molar concentrations between approximately 0.5% and approximately 5%.

FIG. 5 depicts a graph **500** that shows the characterization of the semiconductor **300** by x-ray diffraction (XRD). The graph **500** includes a scan **502** which has peaks **504**, **506**, **508**, and **510**. Each peak corresponds to a material of distinct lattice parameter. The peak **504** corresponds to the intrinsic InGaAsSb layer **306**, and peak **506** corresponds to the p-type InGaAsSb layer **304**. The p-type dopant adds tensile strain to the layer **304** and thus shifts the peak **506** away from the peak **504** by approximately 26 arc-seconds. Peak **508** may correspond to GaAsSb forming at the interface between the p-type GaAs layer **302** and the p-type InGaAsSb layer **304**. The peak **510** corresponds to the substrate **314**. The narrowness of the peaks **504**, **506**, **508**, and **510** indicates that the epitaxial layers **302**, **304**, **306**, **310**, and **312** have high crystallinity and low defect levels.

FIG. 6 depicts a graph **600** that shows XRD scans of intrinsic InGaAsSb layers of different thicknesses epitaxi-

ally formed on GaAs. The layers were grown using molecular beam epitaxy (MBE) at a growth temperature of 440° C. and a Group V element to Group III element ratio (V/III) of 42:1. These layers are coherently strained (non-relaxed) with a bandgap as low as 0.78 eV. The graph 600 includes a scan 602 of a 4 μm layer of InGaAsSb and a scan 604 of a 0.5 μm layer of InGaAsSb. The scan 602 has two peaks, 606 and 608, indicating the presence of two different lattice parameters. The peak 608 corresponds to the GaAs substrate, and the peak 606 corresponds to the 4 μm layer of InGaAsSb. The peak 606 is shifted by -114 arcsec from the peak 608, indicating that the 4 μm layer of InGaAsSb layer is slightly compressive as compared to GaAs. In contrast, the scan 604 only has one peak 610, indicating the presence of only one lattice parameter. The XRD peaks from the 0.5 μm layer of InGaAsSb and the GaAs substrate overlap, indicating that the InGaAsSb layer and the GaAs substrate are lattice matched or nearly matched. Furthermore, the narrowness of the peaks 606, 608, and 610 indicates that the InGaAsSb layers have high crystallinity and low defect levels.

FIG. 7 depicts a graph 700 that shows XRD scans of InGaAsSb layers grown on p-type and semi-insulating GaAs substrates. The graph 700 includes a scan 702 of a 0.5 μm layer of InGaAsSb grown by MBE on a p-type GaAs substrate and a scan 704 of a 0.5 μm layer of InGaAsSb grown by MBE on a semi-insulating GaAs substrate.

Effective substrate temperature control can improve the quality of low-bandgap materials such as InGaAsSb when grown on semi-insulating substrates. As the temperature of a semiconducting substrate is increased, free carriers are thermally generated and its absorption edge shifts to a lower energy. This shift can be measured and used to calculate substrate temperature.

Epitaxial growth systems are often heated using radiant heaters that rely on substrate radiant absorption to raise the temperature of the substrate. Absorption is a function of both doping and bandgap; more absorption occurs as bandgap decreases and/or as doping increases. Layer absorption also scales with layer thickness. As such, growth of a sufficiently thick low-bandgap material such as InGaAsSb on a semi-insulating higher-bandgap material such as a GaAs substrate can result in a situation in which the low-bandgap material dominates radiant absorption. Changes in thickness of this low-bandgap material can thereby significantly affect the substrate temperature.

If a constant heater power which would result in a constant equilibrium temperature for a semi-insulating substrate is maintained while growing a sufficiently thick low-bandgap material, the increase in substrate absorptivity increases the amount of heat absorbed at the constant heater power, resulting in an increase in substrate temperature. Thus, both open-loop temperature control and closed-loop temperature control that is based on indirect measurements of the substrate temperature can be inaccurate when growing sufficiently thick low-bandgap materials on semi-insulating substrates. These effects are not as pronounced when growing low-bandgap materials on more conductive substrates, because doped substrate absorptivities are higher than those for semi-insulating substrates and tend to dominate radiant absorption.

The layer grown on a p-type substrate (scan 702) was grown with closed-loop temperature control that simply regulated the temperature of the substrate holder using a thermocouple positioned to be sensitive to the temperature of the substrate backside (opposite the epitaxial layer growth surface). However, the layer grown on a semi-insulating

substrate (scan 704) was grown with modified closed-loop control. A feedback loop regulated the temperature of the substrate holder using the thermocouple and a first closed-loop control algorithm, but the temperature setpoint of the first closed-loop control algorithm was adjusted by a second closed-loop control algorithm. The second closed-loop control algorithm measured the substrate temperature using the temperature dependence of the substrate's optical absorption edge, and then adjusted the temperature setpoint of the first closed-loop control algorithm to maintain a constant substrate temperature. In this way, the modified closed-loop control algorithm maintained a constant substrate temperature despite changes in the absorptivity of the substrate.

The scan 702 includes a peak 710, and the scan 704 includes peaks 706 and 708. The peaks 706 and 710 are aligned, indicating that temperature was held constant with effective closed-loop control during the growth of the low-bandgap InGaAsSb material. The peak 708 is a secondary peak on the scan 704, and is due to changes in composition resulting from temperature variations during initial growth of the InGaAsSb layer. However, the scans 702 and 704 are well-matched, indicating that with effective temperature control, high-quality InGaAsSb can be grown on a semi-insulating GaAs substrate.

FIG. 8 depicts a graph 800 showing the effect of the In/Sb ratio on carrier properties of InGaAsSb, as measured by the Hall effect. The graph 800 includes a carrier concentration curve 802 and a carrier mobility curve 804. Decreasing In/Sb ratio during deposition below about 6 results in higher carrier concentration, as shown by the curve 802. Increasing the In/Sb ratio during deposition above about 6 does not significantly affect the carrier concentration, also shown by the curve 802. However, hole mobility, as measured by the Hall effect, increases consistently as the In/Sb ratio increases during deposition from 2 to 14, as shown by the curve 804.

FIG. 9 depicts a graph 900 showing the effect of the In/Sb ratio on optical properties of InGaAsSb, as measured by photoluminescence (PL). The graph 900 includes a bandgap curve 902 and a PL intensity curve 904. The bandgap varies between approximately 0.811 eV and 0.803 eV as the In/Sb ratio varies between 2 and 14, with a minimum bandgap at an In/Sb ratio of 10. The PL intensity varies non-monotonically as the In/Sb ratio varies between 2 and 14, with a minimum at an In/Sb ratio of 2 and a maximum at an In/Sb ratio of 6. A higher PL intensity indicates a higher quality InGaAsSb layer.

Lower In/Sb ratios result in lower bandgaps, which can be desirable for certain applications. However, decreasing the In/Sb ratio below about 6 can result in increases in background carrier concentration, which can result in increased dark current. When the InGaAsSb material is used in p-i-n diodes as a photodetector, higher dark current can increase the background noise level, thus reducing the signal-to-noise level. Accordingly, it is desirable to decrease the bandgap while maintaining low background carrier concentrations.

FIG. 10 depicts a graph 1000 that shows the effect of growth temperature and As flux on the carrier concentration of InGaAsSb, as measured by the Hall effect. The graph 1000 includes curves 1002, 1004, and 1006, showing the effect of 25% increases and 25% decreases in As flux on carrier concentration at growth temperatures (i.e., substrate temperatures during growth) of 420° C., 440° C., and 460° C., respectively. Higher growth temperatures result in lower background carrier concentrations. In this study, a growth temperature of 460° C. resulted in a background carrier concentration of approximately  $4 \times 10^{15} \text{ cm}^{-3}$ , as shown by the curve 1006. The As flux has a smaller impact on the



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background carrier concentration, but in general, a lower As flux results in a lower background carrier concentration, as shown by the curves **1004** and **1006**.

FIG. **11** depicts a graph **1100** that shows the effect of growth temperature and arsenic flux on the bandgap of InGaNaSb, as measured by photoluminescence. The graph **1100** includes curves **1102**, **1104**, and **1106**, showing the effect of 25% increases and 25% decreases in As flux on bandgap at growth temperatures of 420° C., 440° C., and 460° C., respectively. The bandgap of InGaNaSb exhibits only a weak dependence on growth temperature between 420° C. and 460° C., ranging from a low of 0.79 eV to a high of 0.82 eV. The bandgap of InGaNaSb also exhibits a weak dependence on As flux, with an As flux of 1 (nominal value) generally resulting in the highest bandgap within the range of fluxes in this study.

FIG. **12** depicts a graph **1200** showing the effect of rapid thermal annealing (RTA) on the carrier concentration of InGaNaSb, as measured by the Hall effect. The graph **1200** includes curves **1202** and **1206** corresponding to an RTA temperature of 780° C., curve **1208** corresponding to an RTA temperature of 800° C., and curves **1210** and **1212** corresponding to an RTA temperature of 820° C. In general, short anneals of InGaNaSb at lower temperatures result in lower background carrier concentrations, within the RTA parameters examined in the study. For a given RTA temperature, a shorter RTA duration resulted in a lower carrier concentration, as shown by curves **1202**, **1206**, **1210**, and **1212**. For a given RTA duration, a lower RTA temperature resulted in a lower carrier concentration, as shown by curves **1202**, **1206**, **1210**, and **1212**. The reduction in carrier concentration with RTA temperature is especially significant. Decreasing the RTA temperature from 820° C. to 780° C. reduces the carrier concentration from  $3 \times 10^{16} \text{ cm}^{-3}$  (curve **1212**) to  $7 \times 10^{14} \text{ cm}^{-3}$  (curve **1202**), a decrease of more than an order of magnitude.

FIG. **13** includes a graph **1300** showing the effect of RTA on the bandgap of InGaNaSb as measured by photoluminescence. The graph **1300** includes curves **1302** and **1306** corresponding to an RTA temperature of 780° C., curve **1308** corresponding to an RTA temperature of 800° C., and curves **1310** and **1312** corresponding to an RTA temperature of 820° C. The effects of RTA on bandgap are similar to the effects on carrier concentration. For a given RTA temperature, a shorter RTA duration resulted in a lower bandgap, as shown by curves **1302**, **1306**, **1310**, and **1312**. For a given RTA duration, a lower RTA temperature resulted in a lower bandgap, as shown by curves **1302**, **1306**, **1310**, and **1312**. Decreasing the RTA temperature from 820° C. to 780° C. reduces the bandgap from approximately 0.81 eV (curve **1312**) to approximately 0.797 eV (curve **1302**).

FIG. **14** depicts a graph **1400** that shows a photoluminescence spectrum of a 0.5  $\mu\text{m}$  layer of InGaNaSb grown on a GaAs substrate. The graph **1400** includes a scan **1402** that was measured on a 0.5  $\mu\text{m}$  layer of InGaNaSb grown on a GaAs substrate. The scan **1402** includes a peak **1404** at a wavelength of 1.5429  $\mu\text{m}$ , corresponding to an energy of 0.8036 eV. The scan **1402** includes a full width at half maximum 1406 of 121.3 nm, a narrow width that indicates good material quality.

FIG. **15** includes a colormap **1500** that shows cross-wafer variation in bandgap of a 0.5  $\mu\text{m}$  layer of InGaNaSb grown on a 150 mm GaAs substrate. The bandgap of the layer ranges between a minimum value of 0.799 eV at a center location **1502** and a maximum value of 0.813 eV at an edge location **1504**. The average bandgap is 0.806 eV, and the standard deviation is 0.408%, or approximately 0.003 eV.

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These variations can be due to variations in precursor flow, substrate temperature, and/or other factors. However, the variations are relatively small and illustrate that the uniformity is good.

FIG. **16** illustrates several examples of p-i-n diodes formed over substrates with lattice parameters matching or nearly matching GaAs. FIG. **16** depicts semiconductors **1600**, **1630**, and **1660**. The semiconductor **1600** includes a p-i-n diode **1602** epitaxially formed over a GaAs substrate **1606**. The GaAs substrate **1606** thus provides an ideal substrate for homoepitaxy of a Ga—As-based p-i-n structure such as the p-i-n diode **1602**. The substrate **1606** can include any of the substrates **114**, **214**, **314**, and **414**. The p-i-n diode **1602** can include any of the p-i-n diode comprising the layers **102**, **106**, and **112**; the p-i-n diode comprising the layers **202**, **206**, **208**, and **212**; the p-i-n diode comprising the layers **302**, **304**, **306**, **310**, and **312**; and the p-i-n diode comprising the layers **402**, **404**, **406**, **408**, **410**, and **412**.

The semiconductors **1630** and **1660** each include a lattice engineered layer over a silicon substrate. Each lattice engineered layer has a first surface nearest the silicon substrate and a second (top-most) surface opposite the silicon substrate. The first surface nearest the silicon substrate has a lattice parameter that is matched or nearly matched to that of Si. This results in a low number of defects and/or dislocations in the lattice engineered layer. The semiconductors **1630** and **1660** can include one or more layers (not shown) between the lattice engineered layer and the silicon substrate. The second surface opposite the silicon substrate has a lattice parameter that is matched or nearly matched to that of GaAs. This results in a low number of defects and/or dislocations when epitaxially growing p-i-n layers and/or dilute nitride layers that have lattice constants that are matched or nearly matched to that of GaAs. A low number of defects can include comparable or fewer defects than would occur in an  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  layer grown on an InP substrate.

The semiconductor **1630** includes a graded  $\text{Si}_x\text{Ge}_{1-x}$  ( $0 \leq x \leq 1$ ) layer **1634** formed over a Si substrate **1635**. The graded  $\text{Si}_x\text{Ge}_{1-x}$  layer **1634** is a lattice engineered layer. The semiconductor **1630** also includes a p-i-n diode **1632** epitaxially formed over the graded  $\text{Si}_x\text{Ge}_{1-x}$  layer **1634**. The Si fraction  $x$  of the graded  $\text{Si}_x\text{Ge}_{1-x}$  layer **1634** varies from 0 to 1 through its thickness. At the interface with the Si substrate **1635**,  $x=1$  and the graded  $\text{Si}_x\text{Ge}_{1-x}$  layer **1634** substantially only contains Si. At the interface with the p-i-n diode **1632**,  $x=0$  and the graded  $\text{Si}_x\text{Ge}_{1-x}$  layer **1634** substantially only contains Ge. Thus, the graded  $\text{Si}_x\text{Ge}_{1-x}$  layer **1634** provides a transition in lattice parameter from that of the Si substrate (5.43 Å) to that of Ge (5.66 Å), which nearly matches to that of GaAs (5.65 Å). The lattice constants of Ge and GaAs are matched well enough that high-quality GaAs can be epitaxially grown on a Ge surface. Thus, the graded  $\text{Si}_x\text{Ge}_{1-x}$  layer **1634** allows growth of GaAs layers on Si substrates. Together, the graded  $\text{Si}_x\text{Ge}_{1-x}$  layer **1634** and the silicon substrate **1635** comprise a substrate **1636** having a top surface with a lattice parameter nearly matching GaAs. The substrate **1636** can include any of the substrates **114**, **214**, **314**, and **414**. The p-i-n diode **1632** can include any of the p-i-n diode comprising the layers **102**, **106**, and **112**; the p-i-n diode comprising the layers **202**, **206**, **208**, and **212**; the p-i-n diode comprising the layers **302**, **304**, **306**, **310**, and **312**; and the p-i-n diode comprising the layers **402**, **404**, **406**, **408**, **410**, and **412**.

The semiconductor **1660** includes a rare earth (RE) containing layer **1664** epitaxially formed over a silicon substrate **1665**. The RE containing layer **1664** is a lattice engineered

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layer. Rare earth elements are a specific class of elements on the periodic table (Sc, Y, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu). The RE containing layer can contain one or more of the rare earth elements. The semiconductor **1660** also includes a p-i-n diode **1662** epitaxially formed over the RE containing layer **1664**. Generically, the RE containing layer can be a rare earth oxide (REO), a rare earth silicide (RESi), or a pnictide (RE-V, where V represents a group V element from the periodic chart, namely N, P, As, Sb, or Bi) or any combination of REO, RESi, and/or pnictide. The composition of the RE containing layer can be selected to result in a lattice parameter matching or nearly matching GaAs at its interface with the p-i-n diode **1662**. For example, the layer at the interface could be  $\text{ErAs}_x\text{N}_{1-x}$ , where x is approximately 0.9, which is lattice matched or nearly matched to GaAs. The rare earth containing layer can be of constant composition or graded throughout its thickness. When graded, the layer can be engineered so that the portion nearest the Si is chemically and mechanically compatible with silicon. For example, gadolinium oxide could be employed at or near the interface between the silicon and rare earth containing layer due to its lattice match with silicon. Thus, the RE containing layer **1664** provides a template for epitaxial growth of the p-i-n diode **1662**. Together, the RE containing layer **1664** and the silicon substrate **1665** comprise a substrate **1666** having a top surface with a lattice parameter matching or nearly matching GaAs.

The substrate **1666** can include any of the substrates **114**, **214**, **314**, and **414**. The p-i-n diode **1662** can include any of the p-i-n diode comprising the layers **102**, **106**, and **112**; the p-i-n diode comprising the layers **202**, **206**, **208**, and **212**; the p-i-n diode comprising the layers **302**, **304**, **306**, **310**, and **312**; and the p-i-n diode comprising the layers **402**, **404**, **406**, **408**, **410**, and **412**.

FIGS. 1-4 depict p-i-n structures with an n-type layer over a substrate, an optional multiplication layer over the n-type layer, an intrinsic absorber layer over the n-type layer or the optional multiplication layer, and a p-type layer over the intrinsic absorber layer. In some examples, however, the order of the layers may be different. For example, the p-type layer may be over the substrate, the intrinsic absorber layer may be over the p-type layer, and the n-type layer may be over the intrinsic absorber layer. In addition, a multiplication layer may optionally be included, either between either the p-type layer and the intrinsic absorber layer or between the intrinsic absorber layer and the n-type layer. The substrates depicted in FIGS. 1-4 and **16** may be n-type, p-type, highly doped, unintentionally doped, insulating, conducting, or a combination of these.

The layers of the semiconductors **100**, **200**, **300**, **400**, **1600**, **1700**, and **1800** can be epitaxially formed with semiconductor processing techniques such as molecular beam epitaxy (MBE), metalorganic chemical vapor deposition (MOCVD), halide vapor phase epitaxy (HVPE), physical vapor deposition (PVD), and/or sputtering. All of the layers of a semiconductor can be formed in a single chamber, or different layers of a semiconductor can be formed in different chambers. For example, epitaxial layers of the substrates **114**, **214**, **314**, **414**, **1606**, **1636**, and **1666** can be formed in a different chamber than epitaxial layers of the corresponding p-i-n diodes. The semiconductors **100**, **200**, **300**, **400**, **1600**, **1700**, and **1800** are then laterally patterned using photolithography, etching, and metal deposition techniques to produce detectors.

From the above description of the method it is manifest that various techniques may be used for implementing the

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concepts of the method without departing from its scope. The described embodiments are to be considered in all respects as illustrative and not restrictive. It should also be understood that the method is not limited to the particular examples described herein, but can be implemented in other examples without departing from the scope of the claims. A first layer described and/or depicted herein as over a second layer can be immediately adjacent to the second layer, or one or more intermediate layers can be between the first and second layers. Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results.

What is claimed is:

1. A semiconductor, comprising:

a substrate with a lattice parameter matching or nearly matching GaAs;

a first doped III-V layer over the substrate;

an absorber layer over the first doped III-V layer, the absorber layer having:

a dilute nitride comprising  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y-z}\text{Sb}_z$  ( $0 \leq x \leq 1$ ;  $0 \leq y \leq 0.1$ ;  $0 < z \leq 0.1667$ ),

an In/Sb ratio of at least approximately 6,

a bandgap between approximately 0.7 eV and 0.95 eV, and

a carrier concentration less than approximately  $1 \times 10^{16} \text{ cm}^{-3}$  at room temperature; and

a second doped III-V layer over the absorber layer.

2. The semiconductor of claim 1 wherein the dilute nitride comprises  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y-z}\text{Sb}_z$  ( $0 \leq x \leq 0.55$ ;  $0 < y \leq 0.1$ ;  $0 < z \leq 0.1$ ).

3. The semiconductor of claim 1, wherein the carrier concentration of the absorber layer is less than approximately  $5 \times 10^{15} \text{ cm}^{-3}$ .

4. The semiconductor of claim 1, wherein the carrier concentration of the absorber layer is less than approximately  $1 \times 10^{15} \text{ cm}^{-3}$ .

5. The semiconductor of claim 1, wherein a thickness of the absorber layer is between approximately 2 micrometers and approximately 10 micrometers.

6. The semiconductor of claim 1, wherein a thickness of the absorber layer is between approximately 3 micrometers and approximately 5 micrometers.

7. The semiconductor of claim 1, further comprising a multiplication layer between the absorber layer and one of the first and second doped III-V layers.

8. The semiconductor of claim 1, wherein the substrate comprises GaAs.

9. The semiconductor of claim 1, wherein the first doped III-V layer is n-type and the second doped III-V layer is p-type.

10. The semiconductor of claim 1, wherein the first doped III-V layer is p-type and the second doped III-V layer is n-type.

11. The semiconductor of claim 1, wherein the absorber layer is p-type.

12. The semiconductor of claim 1, wherein the substrate comprises:

a silicon substrate; and

a lattice engineered layer over the silicon substrate, the surface of the lattice engineered layer opposite the silicon substrate having a lattice parameter that is matched or nearly matched to GaAs.

13. The semiconductor of claim 12, wherein the lattice engineered layer comprises a  $\text{Si}_x\text{Ge}_{1-x}$  layer, with x graded

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from 1 at a surface of the  $\text{Si}_x\text{Ge}_{1-x}$  layer nearest the silicon substrate to 0 at a surface of the  $\text{Si}_x\text{Ge}_{1-x}$  layer opposite the silicon substrate.

14. The semiconductor of claim 12, wherein the lattice engineered layer comprises a rare earth containing layer, the rare earth containing layer comprising one or more of Sc, Y, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and/or Lu.

15. A method of forming a semiconductor, comprising:  
forming a first doped III-V layer over a substrate with a lattice parameter matching or nearly matching GaAs;  
forming an absorber layer over the first doped III-V layer, the absorber layer having:

a dilute nitride comprising  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y-z}\text{Sb}_z$  ( $0 \leq x \leq 1$ ;  $0 < y \leq 0.1$ ;  $0 \leq z \leq 0.1667$ ),

an In/Sb ratio of at least approximately 6,

a bandgap between approximately 0.7 eV and 0.95 eV, and

a carrier concentration less than approximately  $1 \times 10^{16} \text{ cm}^{-3}$  at room temperature; and

forming a second doped III-V layer over the absorber layer.

16. The method of claim 15, wherein the dilute nitride comprises  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y-z}\text{Sb}_z$  ( $0 \leq x \leq 0.55$ ;  $0 < y \leq 0.1$ ;  $0 < z \leq 0.1$ ).

17. The method of claim 15, wherein the carrier concentration of the absorber layer is less than approximately  $5 \times 10^{15} \text{ cm}^{-3}$ .

18. The method of claim 15, wherein the carrier concentration of the absorber layer is less than approximately  $1 \times 10^{15} \text{ cm}^{-3}$ .

19. The method of claim 15, wherein a thickness of the absorber layer is between approximately 2 micrometers and approximately 10 micrometers.

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20. The method of claim 15, wherein a thickness of the absorber layer is between approximately 3 micrometers and approximately 5 micrometers.

21. The method of claim 15, further comprising forming a multiplication layer between the absorber layer and one of the first and second doped III-V layers.

22. The method of claim 15, wherein the substrate comprises GaAs.

23. The method of claim 15, wherein the first doped III-V layer is n-type and the second doped III-V layer is p-type.

24. The method of claim 15, wherein the first doped III-V layer is p-type and the second doped III-V layer is n-type.

25. The method of claim 15, wherein the absorber layer is p-type.

26. The method of claim 15, wherein the substrate comprises:

a silicon substrate; and

a lattice engineered layer over the silicon substrate, the surface of the lattice engineered layer opposite the silicon substrate having a lattice parameter that is matched or nearly matched to GaAs.

27. The method of claim 26, wherein the lattice engineered layer comprises a  $\text{Si}_x\text{Ge}_{1-x}$  layer, with x graded from 1 at a surface of the  $\text{Si}_x\text{Ge}_{1-x}$  layer nearest the silicon substrate to 0 at a surface of the  $\text{Si}_x\text{Ge}_{1-x}$  layer opposite the silicon substrate.

28. The method of claim 26, wherein the lattice engineered layer comprises a rare earth containing layer, the rare earth containing layer comprising one or more of Sc, Y, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and/or Lu.

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