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(54) **QUANTUM WELL LASERS WITH STRAINED QUANTUM WELLS AND DILUTE NITRIDE BARRIERS**

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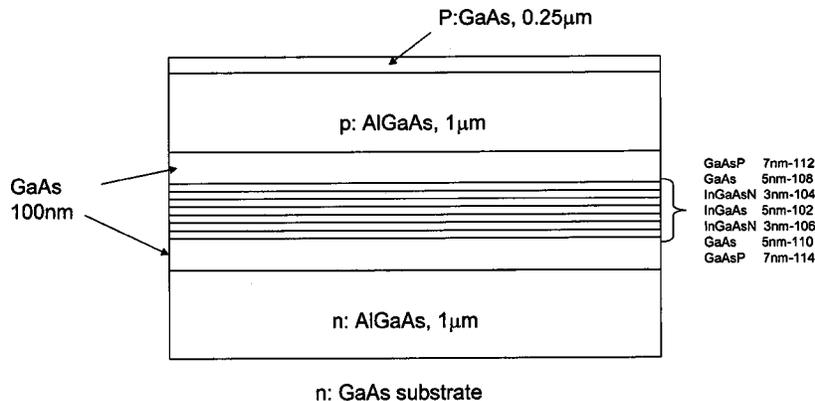
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(57) **ABSTRACT**

In accordance with the present invention, GaAs-based opto-electronic devices have an active region that includes a well layer composed of a compressively-strained semiconductor that is free, or substantially free, of nitrogen disposed between two barrier layers composed of a nitrogen- and indium-containing semiconductor.

20 Claims, 7 Drawing Sheets



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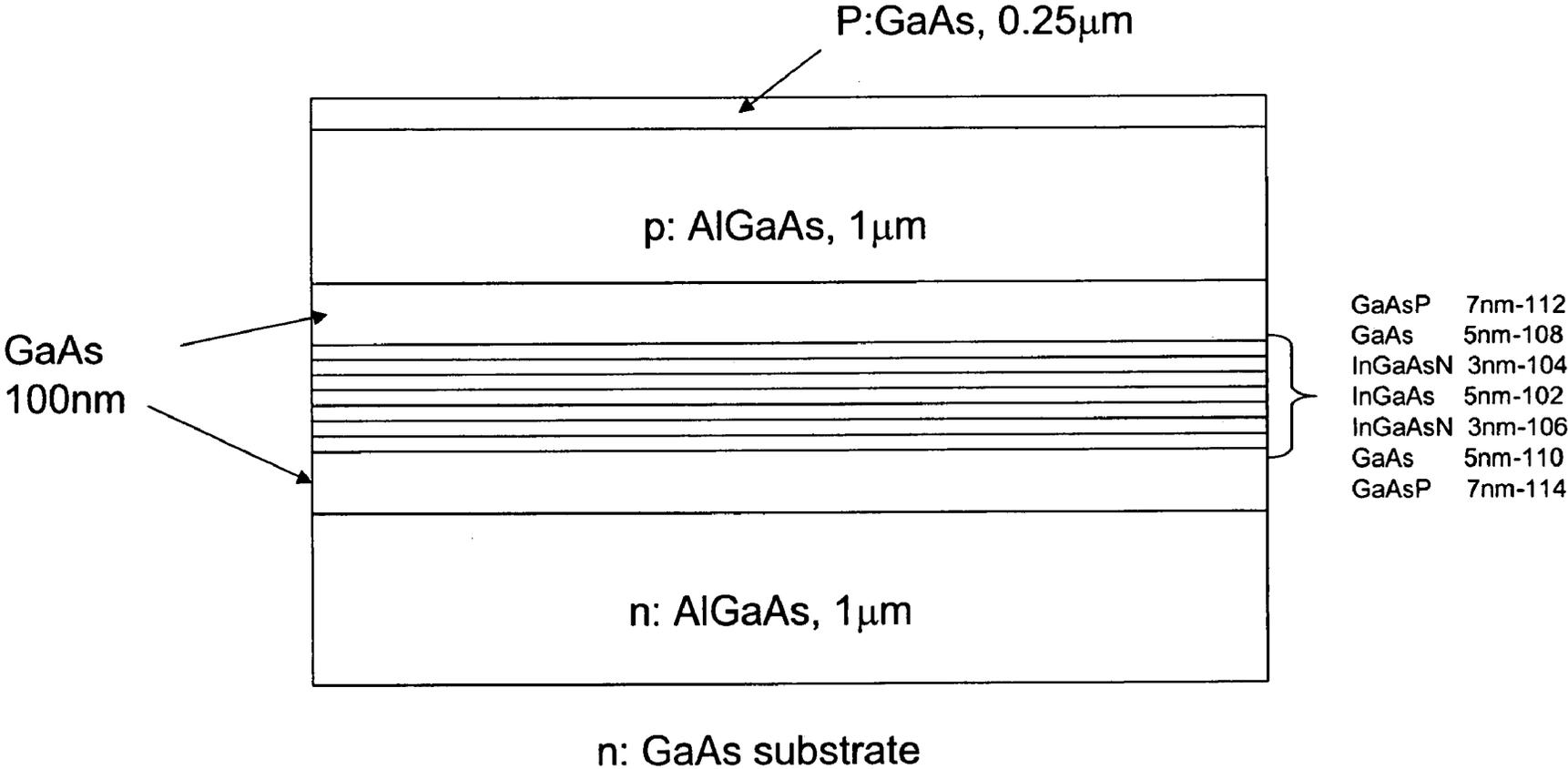
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FIG. 1



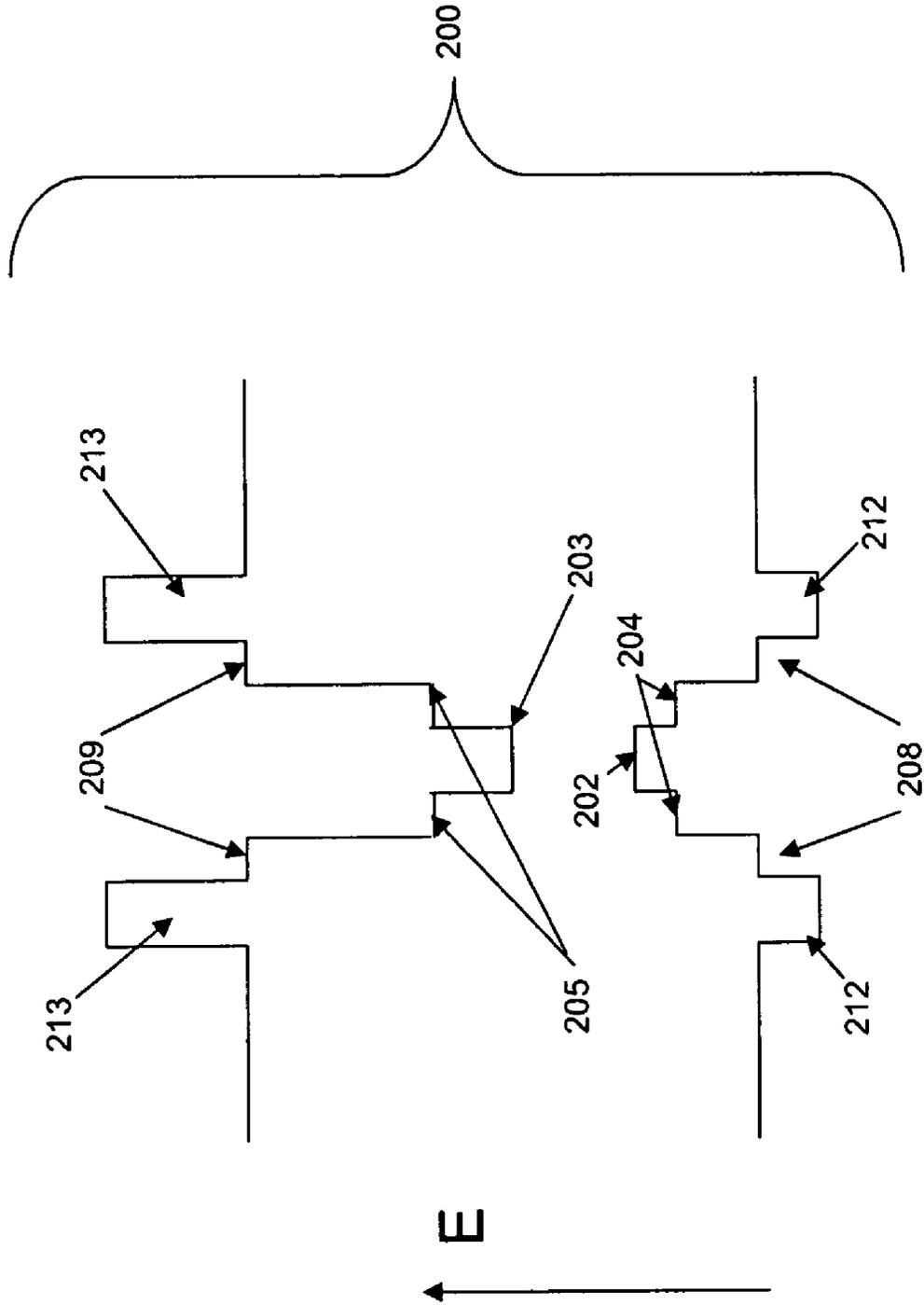


FIG. 2

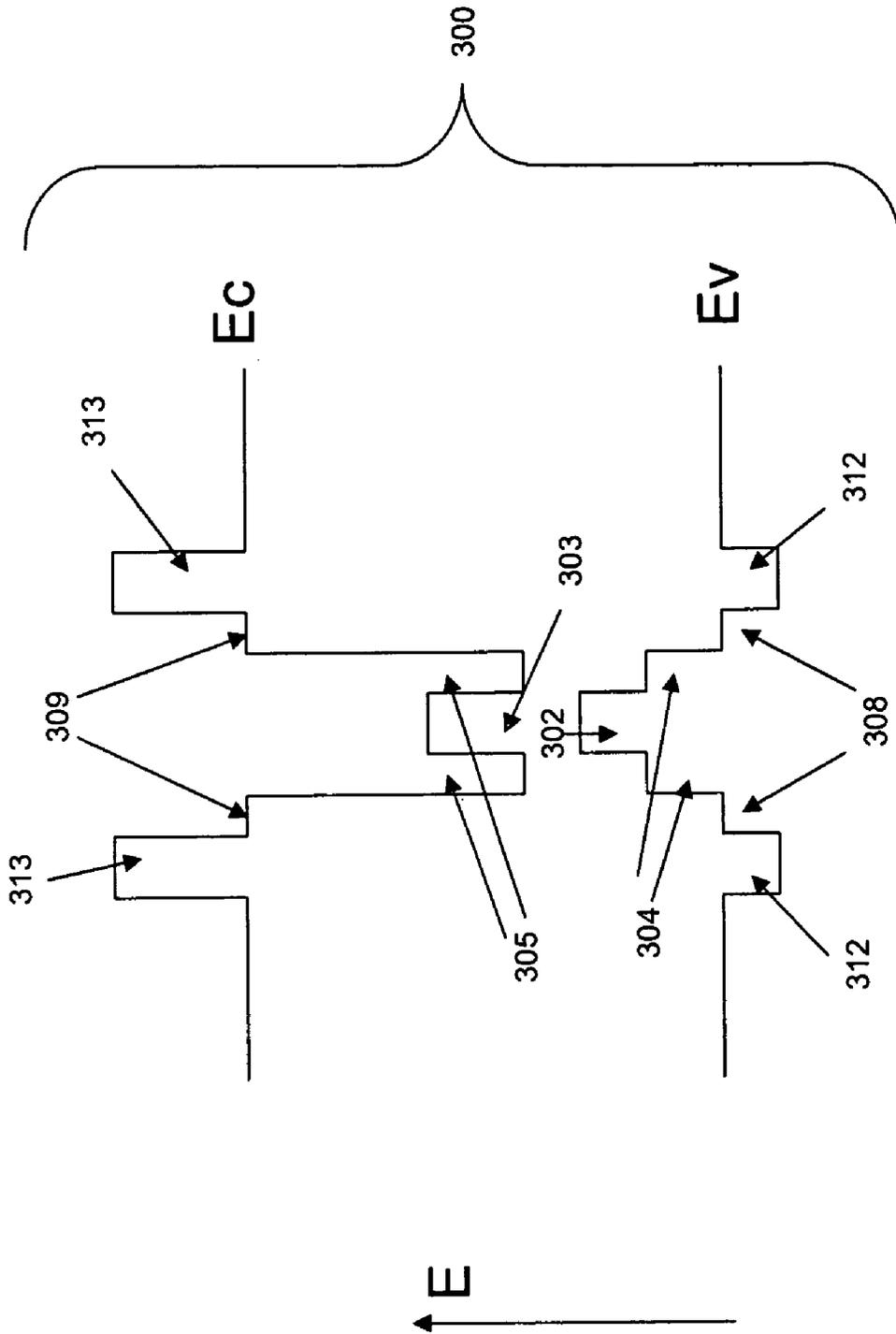


FIG. 3

$k \cdot p$ calculation – $\text{In}_{0.45}\text{GaAs}$ (50Å) / $\text{In}_x\text{GaAsN}_y$ active

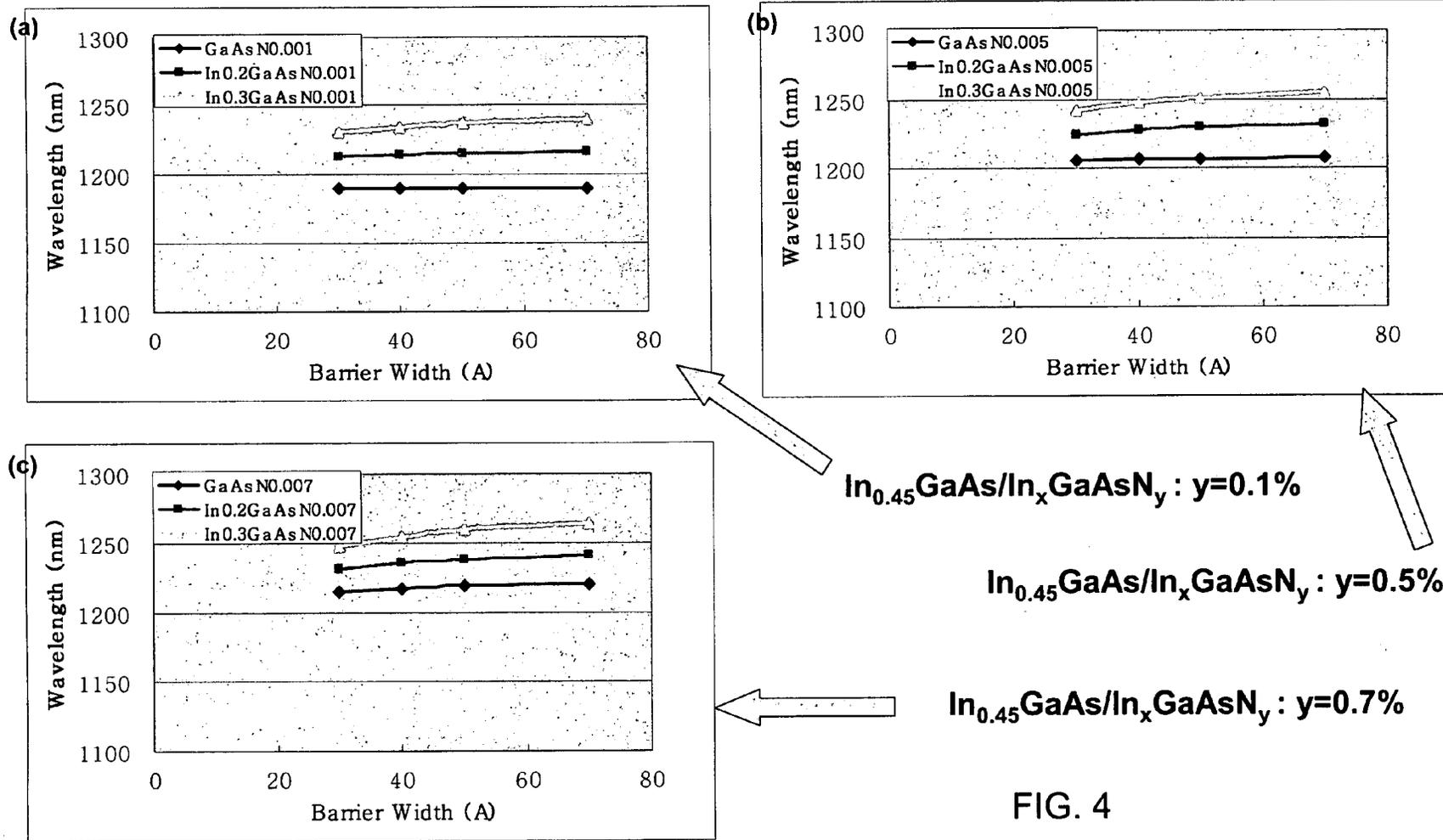


FIG. 4

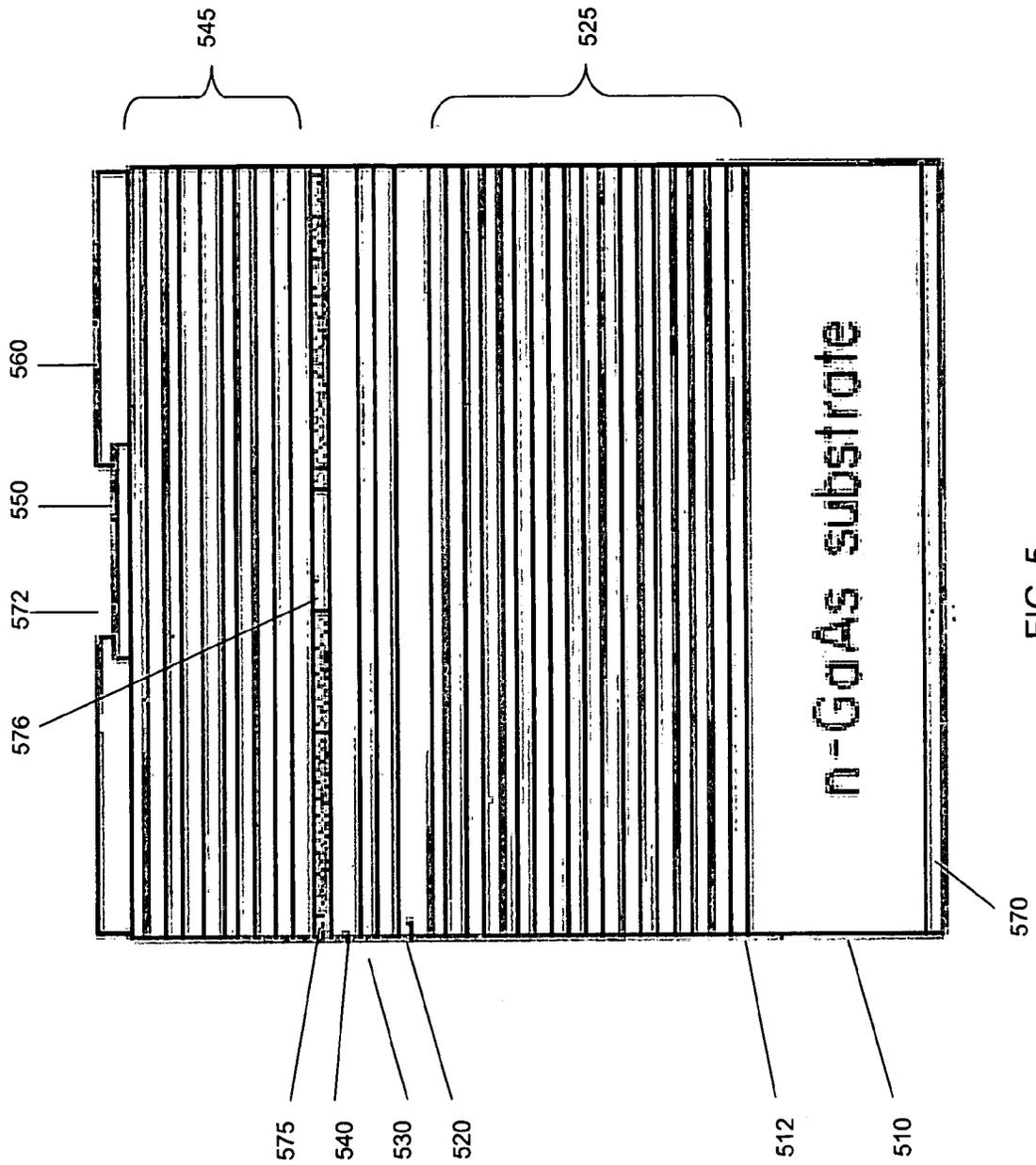
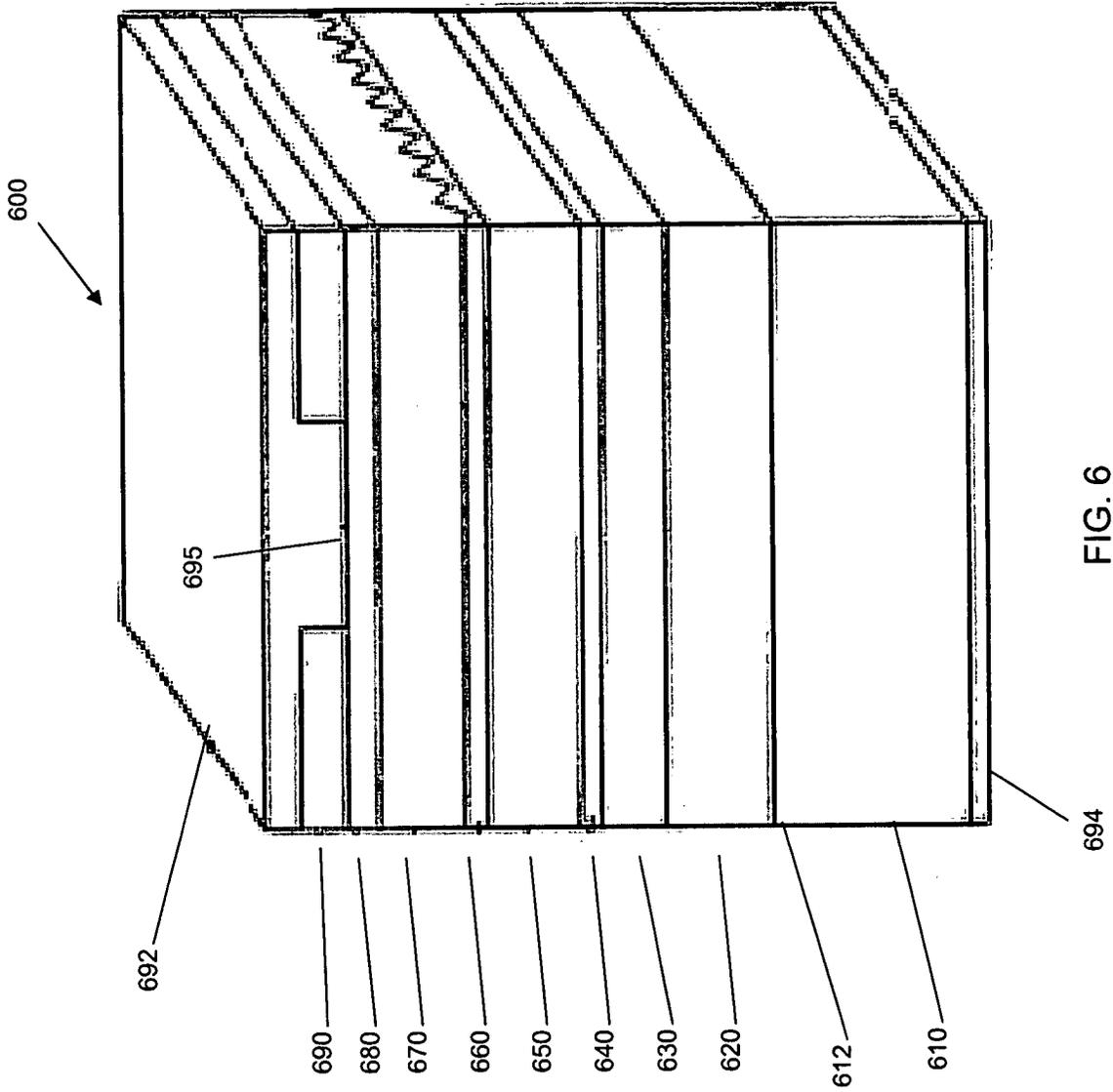


FIG. 5



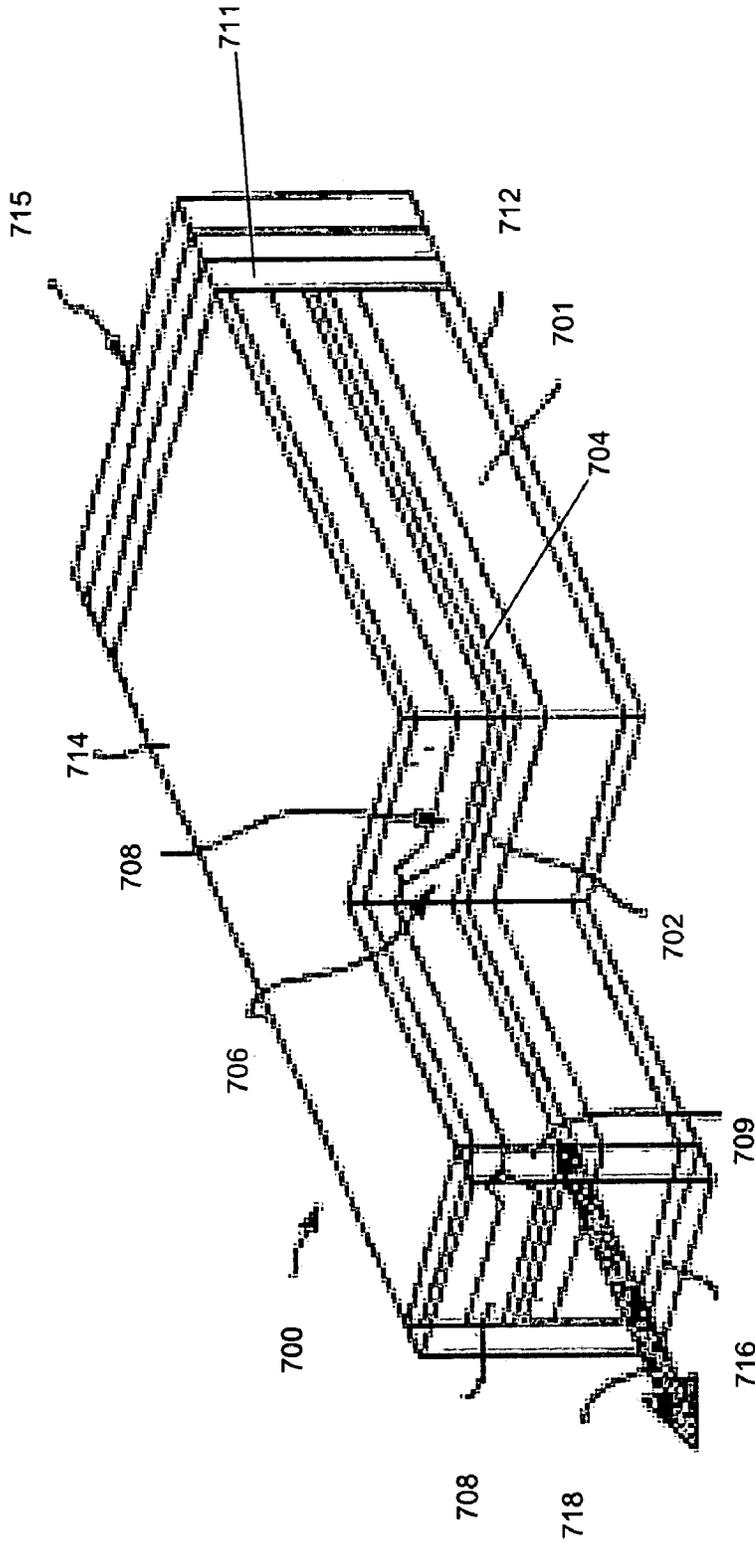


FIG. 7

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QUANTUM WELL LASERS WITH STRAINED QUANTUM WELLS AND DILUTE NITRIDE BARRIERS

STATEMENT OF GOVERNMENT RIGHTS

This invention was made with United States Government support awarded by the following agencies: Department of Defense ARPA under grant number DAAD19-03-1-0367, and National Science Foundation under grant number NSF 0355442. The United States has certain rights in this invention.

FIELD OF THE INVENTION

The present invention relates generally to the field of GaAs-based optoelectronic devices such as light emitting diodes and semiconductor diode lasers incorporating highly strained quantum wells with dilute nitride barriers.

BACKGROUND OF THE INVENTION

Conventional 1300 nm lasers are based on the InGaAsP or InGaAlAs quantum-well (QW) active material system on an InP substrate. Unfortunately, these 1300 nm InP-based diode lasers suffer poor lasing performance at high-temperature operation. (See, Belenky et al, IEEE J. Quantum Electron, vol. 35, pp. 1515, 1999.) The InGaAsN material system has also been introduced as a material system with enormous potential for realizing light emitters on GaAs in the wavelength regime of interest for optical communications, namely 1300-1550. (See, M. Kondow et al., IEEE J. Sel. Top. Quantum Electron, vol. 3, pp. 719, 1997.) The poor temperature characteristics InGaAsN QW lasers, (see, for example, Kondow et al., IEEE J. Sel. Top. Quantum Electron. vol. 3, pp. 719, 1997; Harris Jr., IEEE J. Sel. Top. Quantum Electron. vol. 6, pp. 1145, 2000; and Sato, Jpn. J. Appl. Phys. Part 1 vol. 39, pp. 3403, 2000) as well as other types of 1300 nm active regions on GaAs, as alternatives to realize high-performance QW lasers for high-temperature operation.

Unfortunately, early InGaAsN QW lasers suffer from poor lasing performance due to the utilization of nearly lattice-matched InGaAsN. (See, Kondow et al., IEEE J. Sel. Top. Quantum Electron. vol. 3, pp. 719, 1997 and Harris Jr., IEEE J. Sel. Top. Quantum Electron. vol. 6, pp. 1145, 2000.) The nearly lattice-matched or lattice-matched InGaAsN QW lasers require a relatively large N content of approximately 3% with an In content of 9%-12% to adjust the lattice constant back to that of an unstrained material system. The utilization of a high In-content InGaAsN QW active region has been proposed. (See, Sato, Jpn. J. Appl. Phys., Part 1 vol. 39, pp. 3403, 2000.) The concept proposed was to utilize as high an In content as possible in the InGaAsN QW, such that a minimum amount of N content is required to push the peak emission wavelength to 1300 nm. By utilizing this approach, 1300 nm InGaAsN QW lasers with reasonable threshold current densities, on the order of 0.92-1.0 kA/cm² for devices with a cavity length of approximately 1000 μm have been achieved. Recently, various groups utilizing an In content as high as 30%-40% have been able to realize high-performance InGaAsN QW lasers in the wavelength regime of 1280-1310 nm. (See, for example, Sato, Jpn. J. Appl. Phys., Part 1 vol. 39, pp. 3404, 2000; Livshits et al., Electron. Lett. vol. 36, pp. 1381, 2000; and Tansu et al., IEEE Photonics Technol. Lett. vol. 14, pp. 444, 2000.)

InGaAsN QW lasers with an In content of 40% and N content of only 0.5% have been realized with threshold cur-

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rent densities of only 210 A/cm² at an emission wavelength of 1295 nm. (See, Tansu et al., Appl. Phys. Lett. vol. 81, pp. 2523, 2002.) From studies on InGaAsN QW lasers with an In content of 35%-43%, a trend toward a reduction in the threshold current densities for 1300 nm InGaAsN QW lasers with increasing In content has been observed. Therefore, it is extremely important to realize high-performance InGaAs QW lasers with a very long emission wavelength, such that it requires a minimal amount of N in the QW to push the emission wavelength to 1300 nm.

InGaAs QW lasers with an emission wavelength beyond 1230 nm, utilizing GaAsP tensile-strained buffer and barrier layers have also been realized with threshold current densities of only 90 A/cm². (See, Tansu, et al., Appl. Phys. Lett. vol. 82, pp. 4038 2003.) In these lasers, a tensile-strained GaAsP buffer layer acts to partially strain compensate for the QW growth template leading to an improved optical quality for the highly strained InGaAs(N) QW.

Unfortunately, the use of nitrogen in the quantum wells of the InGaAsN QW lasers decreases the quality of the semiconductor crystal, increasing the risk of device failure.

SUMMARY OF THE INVENTION

In accordance with the present invention, GaAs-based optoelectronic devices have an active region that includes a well layer composed of a compressively-strained semiconductor that is free, or substantially free, of nitrogen disposed between two barrier layers composed of a nitrogen- and indium-containing semiconductor. The present optoelectronic devices are capable of generating light at relatively long wavelengths, e.g., 1.3 μm or higher.

In a preferred embodiment, the active region includes a layer of compressively-strained InGaAs disposed between a pair of InGaAsN barrier layers. The InGaAsN barrier layers may be disposed between a pair of GaAsP tensile-strained barrier layers. In some embodiments, the GaAsP tensile-strained barrier layers are directly adjacent to the InGaAsN barrier layer. In other embodiments, the optoelectronic devices may include a GaAs spacer layer between the InGaAsN barrier layers and the GaAsP tensile-strained barrier layers.

The device preferably includes an active region with multiple well layers in order to increase the optical gain of the device. In such a multiple well layer device, each well layer is disposed between a pair of barriers layers (as well as any optional spacer layers). The resulting active region may be disposed between tensile-strained barrier layers.

The nitrogen containing barrier layers are dilute nitrogen layers, typically having a nitrogen content of no more than about 3%. Depending on the nitrogen content of the barrier layers in the active region, the quantum wells of the active regions may have a type I or a type II structure.

In the devices of the invention, the semiconductor layers that make up the quantum well, barrier, tensile-strained barrier and spacer layers may be epitaxially deposited on a substrate of GaAs using conventional deposition techniques, such as molecular beam epitaxy (MBE) or metal organic chemical vapor deposition (MOCVD).

The present invention may be embodied in various types of optoelectronic devices including amplifiers, light emitting diodes, and edge emitting and surface emitting lasers which incorporate optical feedback to provide lasing action.

Further objects, features and advantages of the invention will be apparent from the following detailed description when taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

FIG. 1 shows a cross-sectional view through a multiple semiconductor layer structure of the single stage of a type I quantum well laser in accordance with the present invention.

FIG. 2 is an energy band diagram for the single stage of the multiple stage quantum well laser of FIG. 1 having a type I quantum well structure.

FIG. 3 is an energy band diagram for the single stage of a multiple stage quantum well laser, in accordance with this invention, having a type II quantum well structure.

FIGS. 4a-4c are graphs showing the k-p calculated emission wavelength for a 50 Å thick active region comprising an In_{0.45}GaAs well layer flanked by InGaAsN tensile-strained barrier layers of various thicknesses having various indium and nitrogen contents.

FIG. 5 is a schematic cross-sectional view of a quantum well laser in accordance with this invention embodied in a vertical cavity surface emitting laser (VCSEL).

FIG. 6 is a schematic diagram of an edge-emitting laser in accordance with another exemplary embodiment of the invention.

FIG. 7 is a schematic diagram of another embodiment of an edge-emitting laser in accordance with the invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention provides high-performance optoelectronic devices with an emission wavelength of 1200 nm, or higher, utilizing nitrogen-free (or substantially nitrogen-free) well layers with dilute nitride barrier layers. Tensile-strained barrier layers disposed beyond the dilute nitride barrier layers are desirably included to provide strain compensation to the compressively-strained InGaAs quantum wells. Spacer layers may separate the tensile-strained barrier layers from the dilute nitride barrier layers. These spacer layers may be used to achieve longer wavelength emission and/or to suppress diffusion between the tensile-strained barrier layers and the dilute nitride barrier layers.

For the purposes of this disclosure a well layer is “substantially free of nitrogen” as long as any nitrogen present in the layer is due only to diffusion between the well layer and a neighboring semiconductor layer. Thus, the term “substantially free of nitrogen” is intended to account for the fact that in practice it may be difficult (or impossible) to prevent some nitrogen from diffusing into the well layer during, for example, an annealing step, even when the well layer is initially deposited without nitrogen. Similarly, for the purposes of this disclosure, a semiconductor layer that is said to include (or comprise) a particular element, such as nitrogen or indium, is a semiconductor layer that is initially formed with that element (as distinguished from a semiconductor layer that includes that element only by virtue of the diffusion of that element from a neighboring semiconductor layer).

The present active regions represent an improvement over more conventional InGaAsN quantum well optoelectronic devices because the elimination of nitrogen from the well layer provides devices with improved crystal quality in the well layer, resulting in improved device performance and reduced risk of device failure. The inclusion of low levels of nitrogen in the dilute nitride barrier layers reduces the quantum size effect for carriers in the quantum well, and results in an extension of emission wavelength. Depending upon the nitrogen content in the dilute nitride barrier layers, the quantum wells of the active region may have a Type I or a Type II band alignment. As the nitrogen content in the dilute nitride

barrier layers increases, the quantum wells undergo a transition from a Type I alignment to a Type II alignment due to the reduction of the bandgap for the dilute nitride semiconductor (e.g., InGaAsN). For the quantum wells that include a InGaAs well layer and InGaAsN_x dilute nitride barrier layers, as shown in FIG. 1 (discussed below), the quantum well adopts a type I configuration when x is less than about 0.8%. For higher N contents, the quantum well adopts a type II configuration.

With reference to the drawings, FIG. 1 shows a cross-sectional view through a multiple semiconductor layer structure (including typical compositions and thicknesses for each layer) that may be incorporated into an optoelectronic device in accordance with the present invention. In the illustrative embodiment shown in FIG. 1, an InGaAs well layer 102 is sandwiched between a pair of InGaAsN barrier layers 104, 106. GaAs spacer layers 108, 110 are disposed adjacent to each InGaAsN barrier layer 104, 106. GaAsP tensile-strained barrier layers 112, 114 are disposed adjacent to each GaAs spacer layer, opposite barrier layers 104, 106.

FIG. 2 shows a schematic energy band diagram 200 for the multiple semiconductor layer structure of FIG. 1. Each layer in the structure of FIG. 1 has an associated valence band and conduction band. InGaAs (e.g., In_{0.45}Ga_{0.55}As) well layer 102 has valence band 202 and conduction band 203; InGaAsN (e.g., In_{0.2}Ga_{0.8}As_{0.993}N_{0.007}) barrier layers 104, 106 have valence bands 204 and conduction bands 205; GaAs spacer layers 108, 110 have valence bands 208 and conduction bands 209; and GaAsP (e.g., GaAs_{0.85}P_{0.15}) tensile-strained barrier layers 112, 114 have valence bands 212 and conduction bands 213. As shown in FIG. 1, the quantum wells in the embodiment have a Type I band alignment.

FIG. 3 shows a schematic energy band diagram 300 for the multiple semiconductor layer structure made from the semiconductor materials shown in FIG. 1, but with a higher nitrogen content in the dilute nitride barrier layers. As shown in the figure, the InGaAs (e.g., In_{0.45}Ga_{0.55}As) well layer has valence band 302 and conduction band 303; InGaAsN (e.g., In_{0.2}Ga_{0.8}As_{0.98}N_{0.02}) layers have valence bands 304 and conduction bands 305; GaAs spacer layers have valence bands 308 and conduction bands 309; and GaAsP (e.g., GaAs_{0.85}P_{0.15}) tensile-strained barrier layers have valence bands 312 and conduction bands 313. As shown in FIG. 3, the quantum wells in the embodiment have a Type II band alignment due to the increased nitrogen content in the dilute nitride barrier layers. In this structure, the InGaAs layer provides a hole quantum well and the InGaAsN layers provide electron quantum wells.

All of the multiple semiconductor layer structures described herein may be fabricated by metal organic chemical vapor deposition (MOCVD) using suitable precursors. Examples of suitable Group III precursors include trimethylgallium, trimethylaluminum and trimethylindium. Examples of suitable Group V precursors include AsH₃ and PH₃. SiH₄ and diethylzinc may be used as n- and p-dopants, respectively. The fabrication of the semiconductor layers is desirably carried out under conditions that minimize or eliminate the diffusion of elements between the layers. For example, this may be accomplished by operating below temperatures at which diffusion occurs.

FIGS. 4a-4c are graphs showing the calculated emission wavelength for a 50 Å thick active region comprising an In_{0.45}GaAs well layer flanked by InGaAsN tensile-strained barrier layers of various thicknesses having various indium and nitrogen contents. As shown in FIGS. 4a-4c, the emission wavelength generally increases with increasing nitrogen content in the InGaAsN barrier layer. The emission wavelength

also increases with increasing indium content in the InGaAsN barrier layer. The emission wavelength calculations shown in FIG. 4 are carried out with a 10-band k-p simulation. As shown in FIGS. 4a-4c, various compositions and thicknesses of the InGaAsN barrier layers can be used with the 50 Å thick InGaAs QWs to achieve an emission wavelength of at least about 1.25 μm.

The multiple semiconductor layer structures described above may be incorporated in various semiconductor optoelectronic device structures, including light emitting diodes, laser diodes, amplifiers, gain sections for external cavity lasers, modulators, and photodetectors. For purposes of illustrating the application of the invention, an example of a surface emitting laser structure is discussed below.

FIG. 5 is a schematic cross-sectional view of an example of the present invention embodied in a vertical cavity surface emitting laser (VCSEL) 500. The VCSEL includes a substrate 510 of n-doped GaAs, a lower confinement layer 520 (of, e.g., GaAs or AlGaAs), an active region layer 530 having a multiple quantum well structure comprising InGaAs well layers, InGaAsN barrier layers and, optionally, GaAsP tensile-barrier layers, as described above, an upper confinement layer 540 (of, e.g., GaAs or AlGaAs) and a capping layer 550 of, e.g., p+-doped GaAs. An upper distributed Bragg reflector (DBR) 545, formed, e.g., of multiple (e.g., 22) alternating layers of AlGaAs/GaAs, and a lower DBR 525 formed, e.g., of multiple (e.g., 40) alternating layers of AlAs/GaAs, provide optical feedback of light in the vertical direction to provide lasing action in the active region. Electrode layers 560 and 570 are formed on the top and bottom surfaces of the structure, respectively, of metal (e.g., Ti/Pt/Al) to provide electrical contacts by which voltage may be applied to the VCSEL to generate lasing in the active region. An aperture or opening 572 is formed in the electrode layer 560 through which a light beam may be emitted. A layer of AlAs/Al₂O₃ 575 with an opening 576 therein interposed between the upper confinement layer 540 and the upper DBR 545 to confine current flow through the opening 576 and provide light generation in the active region under the opening. The top surface 512 of the substrate 510 may be oriented in a (100) crystallographic direction, and the various layers formed above the substrate 510 can be epitaxially grown thereon in a conventional fashion. According to alternative embodiments, other crystallographic directions for the top surface 512 and subsequent layers may be used. The epitaxially-grown layers may be provided above the substrate 510 using metal organic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE).

Implementation of InGaAs/InGaAsN active regions into vertical cavity surface emitting lasers (VCSELs), allows for production of monolithic, lower cost, longer wavelength (e.g., 1.2 to 1.55 μm or longer, etc.) sources, as compared with conventional lasers.

The invention may also be embodied in edge emitting lasers. For purposes of illustration, FIG. 6 shows a schematic diagram of a distributed feedback edge-emitting laser 600 fabricated in accordance with another exemplary embodiment. The laser 600 includes a substrate 610 of n-doped GaAs, a lower cladding layer 620 (e.g., n-doped AlGaAs or n-doped InGaP), a lower optical confinement layer 630 (e.g., GaAs), an active region 640 having a multiple quantum well structure as discussed above, an upper confinement layer 650 (e.g., GaAs), a distributed feedback grating 660 (DFB) formed in the upper confinement layer, an upper cladding layer 670 (e.g., p-AlGaAs or p-InGaP), a capping layer 680 (e.g., p-doped GaAs), an insulating layer 690 (e.g., silicon dioxide), and electrode layers 692 and 694 preferably formed

of a metal to provide electrical contacts through which voltage may be applied to generate light in the active region 640. Although a distributed feedback grating 660 is illustrated for purposes of providing grating feedback, the present invention may be embodied in lasers having mirrored and semi-mirrored edge facets as discussed below. Lateral current confinement may be provided utilizing an opening 695 in the insulating layer 690 through which current can flow from the electrode 692. However, other types of gain guiding and/or lateral confinement may be utilized. The top surface 612 of the substrate 610 may be oriented in a (100) crystallographic direction, and the various layers formed above the substrate 610 may be epitaxially grown thereon. According to alternative embodiments, other crystallographic directions for the top surface 612 and subsequent layers may be used. The epitaxially-grown layers may be provided above the substrate 610 using metal organic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE).

The active region 640 includes a multiple QW structure having, e.g., 3 QW stages, for a total of 6 layers. A different number of stages or layers may be used in an active region. For example, ten layers may be used to form an active region having five QW stages. The thickness and composition of each of the layers included in the active region 640 may be chosen based on the factors discussed above.

An example of an edge emitting Fabry-Perot laser design incorporating the present invention is illustrated generally at 700 in FIG. 7. The laser 700 includes a substrate 701 of GaAs, generally n-doped, an n-doped cladding layer 702 (e.g., AlGaAs or InGaP), a strained multiple quantum well-single confinement heterostructure (MQW-SCH) active region layer 704 in accordance with the invention, an upper p-type cladding layer 706 (e.g., AlGaAs or InGaP), an n-GaAs blocking layer 708 with a central opening 709 therein (e.g., p-AlGaAs), and a cap layer 711 (e.g., p-GaAs). A layer of metal 712 on the bottom surface of the substrate 701 provides the lower electrode, and a layer of metal 714 on the top surface of the cap layer 711 provides the upper electrode. When voltage is applied between the upper electrode 714 and the lower electrode 712, current flows in the opening 709 in the blocking layer 708, with current being blocked elsewhere by the n-p junction provided by the blocking layer 708 and the p-type cladding layer 706. Optical feedback to provide lasing action in the active region is provided by a high reflection coating mirror 715 at one of the edge facets and a lower reflection coating 716 at the other edge facet which provides partial reflection and allows a beam of light 718 to exit from the edge facet of the laser.

It should be understood that the invention is not limited to the embodiments set forth herein as illustrative, but embraces all such forms thereof as come within the scope of the following claims.

What is claimed is:

1. A GaAs-based multiple semiconductor layer structure for an optoelectronic device comprising an active region comprising at least one quantum well, the quantum well comprising a well layer disposed between two dilute nitride semiconductor layers, wherein the well layer comprises a compressively-strained semiconductor comprising indium and being substantially free of nitrogen and the two dilute nitride semiconductor layers comprise indium and nitrogen.
2. The multiple semiconductor layer structure of claim 1, wherein the well layer is a InGaAs layer and the two dilute nitride semiconductor layers are InGaAsN layers.
3. The multiple semiconductor layer structure of claim 2, wherein the two InGaAsN layers are disposed between two tensilely-strained GaAsP barrier layers.

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4. The multiple semiconductor layer structure of claim 3, further comprising a GaAs spacer layer disposed between each InGaAsN layer and each GaAsP barrier layer.

5. The multiple semiconductor layer structure of claim 2, wherein the InGaAs well layer and the InGaAsN layers form a type I quantum well.

6. The multiple semiconductor layer structure of claim 3, wherein the InGaAs well layer, the InGaAsN layers, and the tensilely-strained GaAsP barrier layers form a type II quantum well.

7. The multiple semiconductor structure of claim 1, wherein the active region comprises multiple adjacent quantum wells.

8. A vertical cavity surface emitting laser comprising:

- (a) a GaAs substrate;
- (b) a first mirror disposed above the substrate;
- (c) the active region of claim 1, disposed above the first mirror;
- (d) a layer defining an opening disposed above the active region;
- (e) a second mirror disposed above the layer defining the opening;
- (f) a first electrode disposed below the substrate; and
- (g) a second electrode defining an opening disposed above the second mirror.

9. The vertical cavity surface emitting laser of claim 8, further comprising a lower confinement layer disposed between the active region and the lower mirror and an upper confinement layer disposed between the active region and the layer defining an opening.

10. A distributed feedback edge emitting laser comprising:

- (a) a GaAs substrate;
- (b) the active region of claim 1 disposed above the substrate;
- (c) a distributed feedback grating disposed above the active region;
- (d) a first electrode disposed below the substrate; and
- (e) a second electrode disposed above the distributed feedback grating.

11. The distributed feedback edge emitting laser of claim 10, further comprising a lower confinement layer disposed between the active region and the substrate and an upper confinement layer disposed between the active region and the second electrode, wherein the distributed feedback grating is formed in the upper confinement layer.

12. The distributed feedback edge emitting laser of claim 11, further comprising a lower cladding layer disposed between the lower confinement layer and the substrate and an upper cladding layer disposed between the distributed feedback grating and the second electrode.

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13. An edge emitting Fabry Perot laser comprising:

- (a) a GaAs substrate;
- (b) the active region of claim 1 disposed above the substrate;
- (c) a blocking layer defining an opening disposed above the active region;
- (d) a first electrode disposed below the substrate;
- (e) a second electrode disposed above the blocking layer;
- (f) a first mirror disposed at a first edge facet of the active region; and
- (g) a second mirror disposed at a second edge facet of the active region, opposite the first mirror, wherein the second mirror allows partial reflection of light generated in the active region.

14. The edge emitting Fabry Perot laser of claim 13, further comprising a lower cladding layer disposed between the active region and the substrate and an upper cladding layer disposed between the active region and the blocking layer.

15. A method for forming the GaAs-based multiple semiconductor layer structure of claim 1, the method comprising forming at least one quantum well by:

- (a) depositing a first dilute nitride semiconductor layer over a GaAs substrate, the dilute nitride semiconductor comprising indium and nitrogen;
- (b) depositing a well layer comprising a layer of a semiconductor comprising indium and being substantially free of nitrogen over the first dilute nitride semiconductor layer; and
- (c) depositing a second dilute nitride semiconductor layer over the layer of a semiconductor comprising indium and being substantially free of nitrogen.

16. The method of claim 15, wherein the well layer is a InGaAs layer and the first and second dilute nitride semiconductor layers are InGaAsN layers.

17. The method of claim 16, further comprising depositing a first GaAsP layer over the substrate prior to the deposition of the first InGaAsN layer and depositing a second GaAsP layer over the second InGaAsN layer.

18. The method of claim 17, further comprising depositing a first GaAs layer over the first GaAsP layer prior to the deposition of the first InGaAsN layer and depositing a second GaAs layer over the second InGaAsN layer prior to depositing the second GaAsP layer.

19. The method of claim 16, wherein the InGaAs layer and the first and second InGaAsN layers form a type I quantum well.

20. The method of claim 17, wherein the InGaAs layer, the first and second InGaAsN layers and the first and second GaAsP layers form a type II quantum well.

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