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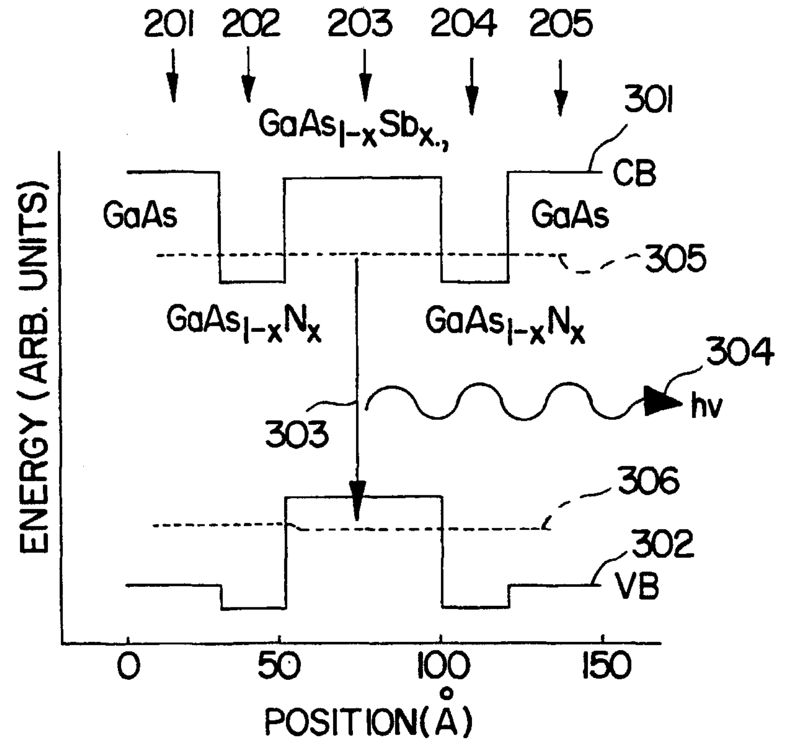
(54) Title: METHOD AND APPARATUS FOR LONG WAVELENGTH SEMICONDUCTOR LASERS



(57) Abstract: A W quantum well structure for active region of semiconductor lasers for long wavelength emission of photons. The energy band lineups in the disclosed heterostructures achieve emission at wavelengths of 1.3 micron or greater. The W quantum well structure and exemplary materials can be applied to any semiconductor laser including a vertical cavity surface emitting laser (VCSEL) (100). The active region (106) is comprised of one or more sets of triad layers of GaAs1-xNx / GaAs1-ySby / GaAs1-xNx to provide the W quantum well structure. The energy band of these materials provides a staggered band alignment which causes electrons and holes to be confined in adjacent layers to one another. Because the wavefunctions associated with these materials tunnel into adjacent layers, optical emission at a longer wavelength is achievable than otherwise available from the energy gaps of the constituent materials alone.

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METHOD AND APPARATUS
FOR
LONG WAVELENGTH SEMICONDUCTOR LASERS

FIELD OF THE INVENTION

The present invention relates generally to semiconductor lasers. More particularly, the present invention relates to heterojunction active regions of semiconductor lasers.

BACKGROUND OF THE INVENTION

Semiconductor lasers have become more important. One of the most important applications of semiconductor lasers is in communication systems where fiber optic communication media is employed. With growth in electronic communication, communication speed has become more important in order to increase data bandwidth in electronic communication systems. Improved semiconductor lasers can play a vital roll in increasing data bandwidth in communication systems using fiber optic communication media. A preferred component for optical interconnection of electronic components and systems via optical fibers is a semiconductor laser known as a vertical cavity surface emitting laser (VCSEL). Referring to Figure 1A, a prior art vertical cavity surface emitting laser (VCSEL) 100 is illustrated. VCSEL 100 is cylindrical in shape and includes heterojunctions of semiconducting materials. When VCSEL 100 is lasing, a laser light is emitted from the top surface in a region defined by the optical confinement region 103. When lasing, the VCSEL 100 has a transverse mode field 108 and a longitudinal mode field 109. VCSEL 100 includes a first terminal 101 and a second terminal 102 coupled respectively to the top and bottom surfaces of the VCSEL to provide current and power. VCSEL 100 includes distributed Bragg reflector (DBR) layers 104A and 104B defining the optical confinement region 103. The optical confinement region 103 provides optical confinement such that the light can be reflected between the DBR layers 104A and 104B in a reinforcing manner to provide light amplification. The optical confinement region 103 is a cylindrical region having a diameter of D. VCSEL 100 includes heterojunction semiconductor layers 105. The region of the heterojunction semiconductor layers 105 which overlaps with the optical confinement region is referred to as the active region 106. The active region 106 provides current confinement so as to provide lasing when a threshold current is supplied to the VCSEL 100. Threshold current is the current level required for injecting enough carriers (electrons and holes) for lasing to occur. The frequency and wavelength of the light emitted from a VCSEL is a function of the structure and composition of materials of the active region 106. The typical structure of the heterojunction semiconductor layers 105 and active region 106 includes one or more pairs of quantum wells. Quantum wells are formed from particular semiconductor materials having a thickness of around one hundred Angstroms or less where the quantum confinement effects become important. Under quantum confinement effects, the effective bandgap of the quantum well material increases with decreasing thickness. Surrounding the one or more pairs of quantum wells are semiconductor materials that provide cladding and barriers. Quantum wells are key components in laser diodes in that they can strengthen electro-optical interactions by confining carriers to small regions.

To improve optical confinement, index guiding may be used. Index guiding uses layers of different compounds and structures to provide a real refractive index profile to guide the light. Alternatively a VCSEL may be gain guided. In gain guiding, the carriers induce a refractive index difference which is a function of the laser current level and output power.

VCSELs emit a coherent light beam of light from the surface of the wafer in which they are fabricated owing to the presence of the vertical optical cavity (the optical confinement region 103) formed by the two distributed Bragg reflectors (DBR) 104A and 104B on either side of a gain region (the active region 106). VCSELs are most often formed by epitaxial growth of the DBRs 104A and 104B and the active region 106 on a single crystal semiconductor wafer. In a VCSEL, the number of defects in its layers is minimized when they are grown on a substrate with the same lattice constant and crystal structure. To manufacture a VCSEL in this manner, there are a limited number of materials that can be incorporated into VCSEL devices that have the high performance properties required for lasing. The DBRs 104A and 104B in VCSEL 100 typically consists of alternating quarter wavelength thick layers of materials with different indices of refraction. The larger the difference in index of refraction, the fewer will be the number of layers required to achieve the necessary reflectivity. Gallium-Arsenide/Aluminum-Gallium-Arsenide (GaAs/AlGaAs) materials have to present been the most successful for use in VCSEL structures due to their wide differences in refractive indices. While GaAs/AlGaAs materials are the preferred materials for the DBRs 104A and 104B, they are not suitable for fabricating an active region 106 providing photon emission at longer wavelengths, such as the 1.3 μm or 1.55 μm wavelength standards that are well suited to optical fiber loss and dispersion minima. Heretofore, there have been no suitable materials or composition of materials in which to fabricate VCSELs at these longer wavelengths such as the 1.3 μm or 1.55 μm wavelength standards.

Prior art attempts to fabricate 1.3 μm VCSELs on GaAs have focused on replacing the active region 106 with new heterojunction semiconductor layers 105 of material that emit photons at wavelengths of 1.3 μm. These attempts include providing Gallium-Arsenide-Antimonide (GaAsSb) quantum wells, Gallium-Indium-Nitrogen-Arsenide (GaInNAs) quantum wells, or Indium-Arsenide (InAs) or Indium-Gallium-Arsenide (InGaAs) quantum dot active regions. In the case of the GaAsSb quantum wells, the thickness of the quantum well layer and its Antimony (Sb) composition need to be maintained below the elastic strain limit to avoid defect formation. This constraint also limits the achievable photon emission wavelength to less than the desired 1.3 μm. GaInNAs quantum wells can in principle be grown to emit at 1.3 μm with arbitrary thicknesses on GaAs substrates, if, the Indium (In) and Nitrogen (N) compositions can be controlled to match the lattice constant of GaAs. However, the limitation in Nitrogen (N) composition has limited the photon emission wavelength to less than the desired 1.3 μm. Regarding InAs or InGaAs quantum dot active regions, current manufacturing is unable to achieve high enough density of dots in order to sustain laser operation in a VCSEL.

Increased strain in the materials of the heterojunction 105 and active region 106 of semiconductor lasers has been used to reduce threshold currents and optical losses. Strain is generally produced by changing the concentration ratio of atoms forming the materials of the heterojunction 105. There are two types of strain in the materials, tensile strain and compressive strain. Cladding layers of the quantum well are usually lattice matched to the substrate with respect to strain while the barrier layers may have the opposite strain of the quantum well layer. Strained layer quantum well structures may be employed to try to achieve longer wavelength emission of photons. However, with the increased strain in the quantum well, there is a growth in lattice mismatched active regions which presents limits to the achievable wavelength ranges. For example, consider InGaAs or GaAsSb quantum wells used alone as the active region, which are limited to a laser emission wavelength between 1.1 and 1.25 μm respectively. As the In or Sb composition is increased the layer thickness must be decreased in order to remain within the elastic strain limit. Unfortunately, the quantization energy in the quantum well increases approximately quadratically as the well thickness decreases and thus the emission wavelength saturates. Recently the possibility of using strain compensation and graded quantum wells to extend the emission wavelength of InGaAs quantum wells has been explored. However, this approach only enabled the extension of the emission wavelength to 1.2 μm. Further increases in the photon emission wavelength using this approach appear unfeasible.

It is desirable to overcome the limitations in the prior art and provide new heterojunction semiconductor layers of material that can provide an active region which can lase at a wavelength of 1.3 μm or more.

BRIEF SUMMARY OF THE INVENTION

Briefly, the present invention includes a method, apparatus and system as described in the claims. A W quantum well structure is provided by the present invention to enhance the active region of semiconductor lasers in order to provide long wavelength emission of photons. The present invention provides an active region, incorporating the W quantum well structure, for semiconductor lasers with energy band lineups in heterostructures to achieve emission at wavelengths of 1.3 μm or greater. Application of the active region to a basic laser diode device, a VCSEL, and exemplary materials are disclosed which can be used to achieve lasing at wavelengths of 1.3 μm and greater. The active region is comprised of one or more sets of triad layers of $GaAs_{1-x}N_x$ / $GaAs_{1-y}Sb_y$ / $GaAs_{1-x}N_x$ to provide the W quantum well structure. The energy band of these materials provides a staggered band alignment which causes electrons and holes to be confined in adjacent layers to one another. Because the wavefunctions associated with these materials tunnel into the adjacent layers, optical emission at a longer wavelength is achievable than otherwise available from the energy gaps of the constituent materials alone.

BRIEF DESCRIPTIONS OF THE DRAWINGS

Figure 1 is a three dimensional diagram of a prior art VCSEL.

Figure 2A is a cross sectional view of the heterojunction semiconductor layers forming the active region having the W-shaped quantum well system of a first embodiment of the present invention.

Figure 2B is a cross sectional view of a semiconductor laser having multiple W quantum wells of the present invention.

Figure 3 is an energy band diagram illustrating the optical transition and staggered energy band lineup in the W-shaped quantum well of the first embodiment of the present invention.

Figure 4 is a wavefunction diagram illustrating the electron and hole wavefunctions for the W-shaped quantum well system of the present invention.

Figure 5 is a combined graph of the achievable transition wavelengths and the wavefunction of electrons and holes versus the GaAsN quantum well thickness for the W-shaped quantum well system of the present invention.

Figure 6 is an energy band diagram illustrating an alternate embodiment of a quantum well structure for the present invention for providing photon emission at long wavelengths.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

In the following detailed description of the present invention, numerous specific details are set forth in order to provide a thorough understanding of the present invention. However, it will be obvious to one skilled in the art that the present invention may be practiced without these specific details. In other instances well known methods, procedures, components, and circuits have not been described in detail so as not to unnecessarily obscure aspects of the present invention.

A new quantum well structure is provided by the present invention to enhance the active region of semiconductor lasers in order to provide long wavelength emission of photons. Longer wavelength semiconductor laser diodes improve fiber optic communication systems by overcoming deficiencies in fiber optic fibers that are sensitive in the shorter wavelengths of photon emissions. The new quantum well structure of the present invention overcomes the shortcomings of the prior art by using an active region that relies on energy band lineups in heterostructures to achieve emission at 1.3 μm and longer, rather than the absolute value of energy gaps. The new quantum well structure employs advances of the last few years in the design, fabrication and implementation of so-called staggered offset or type II heterojunction laser diode devices, particularly mid IR laser semiconductor diodes. A basic device concept and example materials which can be used for 1.3 μm and longer VCSELs is disclosed. The active region of the device is comprised of one or more sets of triad layers of $GaAs_{1-x}N_x$ / $GaAs_{1-y}Sb_y$ / $GaAs_{1-x}N_x$ to provide the new quantum well structure. The energy band of these materials provides a staggered band alignment. The staggered band alignment causes electrons and holes to be confined in adjacent layers to one another. Because the wavefunctions associated with these materials tunnel into the adjacent layers, it is possible to achieve optical emission at longer wavelength than the energy gaps of the constituent materials.

Referring now to Figure 2A, a structure of heterojunction semiconductor layers 105′ of materials of the present invention with one set of triad layers $GaAs_{1-x}N_x$ / $GaAs_{1-y}Sb_y$ / $GaAs_{1-x}N_x$ is illustrated. Figure 2A illustrates heterojunction semiconductor layers 105′ and VCSEL 100′ turned sideways in comparison with layers 105 of VCSEL 100 in Figure 1. From reference point P, the first layer of layers 105′ is GaAs 201 which is approximately twenty five angstroms thick. GaAs 201 acts both as a cladding and barrier material for the quantum wells of layers 105′ and active region 106′. The second layer of layers 105′ is Gallium-Arsenide-Nitride ($GaAs_{1-x}N_x$) 202, with the ratio of atoms indicated by the subscript x which can vary over the range of 0.01 to 0.3. The thickness of $GaAs_{1-x}N_x$ 202 is variable depending upon the desired properties of the semiconductor laser but in the preferred embodiment it is approximately thirty angstroms. The layer of $GaAs_{1-x}N_x$ 202 acts an an electron well for electrons and a hole barrier for holes. The layer of $GaAs_{1-x}N_x$ 202 is the central layer for the first quantum well of a pair of quantum wells in the W quantum well materials structure. The third layer of layers 105′ is Gallium-Arsenide-Antimonide ($GaAs_{1-y}Sb_y$) 203, with the ratio of atoms indicated by the subscript y which can vary over the range of 0.01 to 0.5. The thickness of $GaAs_{1-y}Sb_y$ 203 is also variable depending upon the desired properties of the semiconductor laser but in the preferred embodiment it is approximately fifty angstroms. The layer of $GaAs_{1-y}Sb_y$ 203 acts as an electron barrier and a hole well located between the pair of quantum wells formed from $GaAs_{1-x}N_x$. The fourth layer of layers 105′ is Gallium-Arsenide-Nitride ($GaAs_{1-x}N_x$) 204 which is similar to the second layer of layers 105′, $GaAs_{1-x}N_x$ 202. The $GaAs_{1-x}N_x$ 204 is the central layer of the second quantum well of the pair of quantum wells. The layer of $GaAs_{1-x}N_x$ 204 also acts an an electron well for electrons and a hole barrier for holes. The thickness and ration of atoms of $GaAs_{1-x}N_x$ 204 is similar to the thickness and ratio of atoms of $GaAs_{1-x}N_x$ 202 depending upon the desired properties of the semiconductor laser. The thickness of $GaAs_{1-x}N_x$ 204 in the preferred embodiment is approximately thirty angstroms. The layers 105′ and active region 106′ of the semiconductor laser may have additional sets of triad layers of $GaAs_{1-x}N_x$ / $GaAs_{1-y}Sb_y$ /$GaAs_{1-x}N_x$. The final layer of layers 105′ is GaAs 205, similar to GaAs 201, which is approximately twenty five angstroms thick. GaAs 205 also acts both as a cladding and barrier material for the quantum wells of layers 105′ and active region 106′. The quantum well structure of layers 105′ is referred to herein as a W quantum well (WQW). The heterojunction semiconductor layers 105′ of the active region 106′ constructing the W quantum well can be formed in a number of ways including molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD).

Referring now to Figure 2B, a structure of heterojunction layers 105″ of materials of the present invention with multiple sets of triad layers $GaAs_{1-x}N_x$ / $GaAs_{1-y}Sb_y$ / $GaAs_{1-x}N_x$ is illustrated. Heterojunction layers 105″ includes GaAs layers 201 and 205 sandwiching N multiple W quantum wells 210A-210N. The optical confinement region 103 overlapping the heterojunction layers 105″ forms the active region 106″. W quantum well 210A includes GaAsN layer 202A and GaAsSb layer 203A and a portion of GaAsN layer 202B of the next quantum well 210B. W quantum well 210B includes GaAsN layer 202B, GaAsSb layer 203B and a portion of GaAsN layer 202C of the next quantum well 210C. The multiple W quantum well structure can completed repeating this structure until the last of the multiple W quantum wells, W quantum well 210N. W quantum well 210N includes GaAsN layer 202N, GaAsSb layer 203N and GaAsN layer 204. In the multiple W quantum well structure, interior GaAsN layers are shared by adjacent W quantum wells. The multiple W quantum well structure can enhance the gain of the semiconductor laser to alleviate a reduction in gain due to less overlap between electron and hole wavefunctions.

Referring now to the energy band diagram of Figure 3, the conduction band 301 and the valence band 302 are estimated for the layers 105′ and active region 106′ illustrated in Figure 2A. The zero position along the X-axis in Figure 3 corresponds to position P along the X-axis of Figure 2A. This alignment in energy bands is estimated for the material system of layers 105′ and active region 106′ of Figure 2A having an N concentration of 3%, where subscript x is 3%, and an Sb concentration of 30 %, where subscript y is 30%. Other atom concentrations of N and Sb may be used. The quantum well structure results in the shape of the conduction band 301 being similar to the letter W near the light emitting region and thus is referred to as a W quantum well (WQW). The expected optical transition 303 is also illustrated in Figure 3 generating a photon 304 having an energy of hν, where ν equals the speed of light divided by the wavelength (c/λ). Thus, for longer wavelengths of desired emission, it is desirable to have lasing occur within a semiconductor diode with lower energy photons.

The staggered alignment of the energy bands for these materials causes electrons and holes to be confined in adjacent layers to one another. Electrons are localized in the GaAsN layers 202 and 204 and holes are localized in the GaAsSb layer 203. The conduction band offset that confines the electrons in the GaAsN layers 202 and 204, contributes to localization of the electron. As a result, the electron energy states are quantized and lie at an electron energy level 305 which is greater than the conduction band minimum of the conduction band 301. Similarly, the holes are confined forming hole states that are quantized in the GaAsSb layer 203 resulting in a hole energy level 306 which is less than the valence band maximum of the valence band 302, although the energy shift is smaller for holes. In spite of this localization, there is considerable tunneling of the electron states into the GaAsSb layer 203 that, under proper design, can result in significant spatial overlap between electron and hole wavefunctions.

Referring now to Figure 4, the hole wave function ψ_h 400 and various electron wavefunctions ψ_e 401-405 are illustrated for the W quantum well structure of Figure 2A. The position of materials in Figure 4 does not exactly coincide with the position of materials in Figures 2 and 3, due to the variations in thicknesses of the GaAsN layers. The overlap in the hole wavefunction and the electron wavefunction is the interaction that permits efficient optical emission and gain to occur for a semiconductor laser. It is desirable to maximize the overlap between the hole wavefunction and the electron wavefunction in order to maximize the recombination of holes and electrons to produce photons. The greater the overlap between the hole and electron wavefunctions generally means the higher gain achievable within the semiconductor laser. The various electron wavefunctions ψ_e 401-405 plotted in Figure 4 are a function of the thickness of the GaAsN layers 202 and 204. Electron wavefunctions ψ_e 401, 402, 403, 404 and 405 correspond respectively to thicknesses for the GaAsN layers 202 and 204 of ten, twenty, thirty, forty, and fifty angstroms. The electron wavefunction ψ_e 401 provides a larger overlap with the hole wavefunction ψ_h 400. Thus, the energy positions of the states involved are not only a function of the selected materials but are also a function of the layer thicknesses of the W quantum well. Therefore, depending upon the selection of thicknesses, a wide range of emission wavelengths is possible in the materials system (the triad layers of $GaAs_{1-x}N_x$ / $GaAs_{1-y}Sb_y$ /$GaAs_{1-x}N_x$) of the W quantum well. As illustrated in Figure 4, the wavefunctions tunnel into the adjacent layers of materials. Therefore, it is possible to achieve optical emission at longer wavelengths than from the energy gaps of the constituent materials alone.

Referring now to Figure 5, a chart estimating the range of emission energies that can be achieved with the materials system of the W quantum well structure of Figure 2A is illustrated. The chart in Figure 5 combines the plots of wavefunction overlap (ψ_e/ψ_h) and emission energy (hν or wavelength λ where ν equals c/λ) for various thicknesses of GaAsN material. Curves 501, 502 and 503 illustrate the wavefunction overlap versus GaAsN 202 and 204 thickness for N compositions of 1%, 2%, and 3% respectively. Curves 511, 512 and 513 illustrate the energy (wavelength) versus GaAsN 202 and 204 thickness for N compositions of 1%, 2%, and 3% respectively. As can be seen in Figure 5, the concentration of N is very important to the photon emission of the semiconductor laser having a W quantum well structure. The energies illustrated in Figure 5 are estimated on the basis of known energy band parameters and offsets as well as linear interpolations between the end points in composition ranges. In the case of the band offsets between GaAsSb 203 and GaAsN 202 and 204, the transivity rule is used in which the valence band offsets between each of the constituents with GaAs 201 and 205 is used to calculate the offset between them. Because some of the information for the energy estimates is incomplete or controversial, the most conservative estimate of the offset regarding the potential for long wavelength emission has been used. The W quantum well structure and materials system has the potential for emission and laser operation over the range of energies having wavelengths from 1.2 to 1.7 μm. As the wavelength increases, however, the spatial overlap between the electron and hole states decreases owing to greater localization of the electron and holes in their respective confining potentials. In other words, to achieve longer wavelength emission of photons it is desirable to decrease the energy difference (hν) which in turn reduces the overlap between the hole and electron wavefunctions. Nonetheless, it is possible to achieve emission at 1.3 μm with more than 50% spatial overlap (see 3% N concentration with a GaAsN thickness of 15 angstroms). While 50% spatial overlap is expected to provide a reduced gain over other quantum well structures, this can be compensated by utilizing additional sets of the triad layers of $GaAs_{1-x}N_x$ / $GaAs_{1-y}Sb_y$ /$GaAs_{1-x}N_x$ of the W quantum well structure. The W quantum well provides a feasible migration path to 1.55 μm wavelength VCSEL's on GaAs substrates if suitable material parameters are chosen.

One advantage to the triad layers of $GaAs_{1-x}N_x$ / $GaAs_{1-y}Sb_y$ /$GaAs_{1-x}N_x$ of the W quantum well is that lasing can occur in semiconductor lasers with the emission of photons having long wavelengths between 1.2 to 1.7 microns. Another advantage to the triad layers of $GaAs_{1-x}N_x$ / $GaAs_{1-y}Sb_y$ /$GaAs_{1-x}N_x$ of the W quantum well is that they are compatible with the well developed AlGaAs/ GaAs epitaxial mirror technology.

Another advantage of the W quantum well materials system is that strain management is automatically accomplished because GaAsN is tensile strained while GaAsSb is compressively strained. This results in alternately strained material between adjacent layers. GaAsN is the only III-V material with a smaller energy gap than GaAs that has a smaller lattice constant as well. This results from the strong bowing of the energy gap in this material. Thus, the combined triad layers of $GaAs_{1-x}N_x$ / $GaAs_{1-y}Sb_y$ /$GaAs_{1-x}N_x$ of the W quantum well are more weakly strained than single quantum wells would be and additional sets of triad layers can be incorporated into a semiconductor laser in order to compensate for an expected reduced gain without exceeding the elastic strain limit of the materials. The concentration of Nitride and Antimony can effect the strain placed on the materials of W quantum wells. Thus, an even longer wavelength may be achieved by increasing the strain on the materials of the W quantum well.

Referring now to the energy band diagram of Figure 6, a conduction band 601 and a valence band 602 for an alternate embodiment of the W quantum well for the heterojunction 105′ and active region 106′ is illustrated. In this alternate embodiment, the first layer is Aluminum-Gallium-Arsenide (AlGaAs) 201′. The AlGaAs 201′ acts both as a cladding and barrier material for the W quantum well structure. The second layer, layer 202′, is one of a set of three materials. Layer 202′ may be Aluminum-Gallium-Arsenide (AlGaAs), Indium-Gallium-Phosphide (InGaP), or Indium-Gallium-Arsenide-Phosphide (InGaAsP). The energy bands 601 and 602 in Figure 6 are illustrated with the second layer, layer 202′, being Indium-Gallium-Arsenide-Phosphide (InGaAsP). The second layer, layer 202′ acts an an electron well for electrons and a hole barrier for holes. The second layer 202′ is the first layer of a quantum well of a pair of quantum wells. The third layer is Gallium-Arsenide-Antimonide (GaAsSb) 203′. The layer of GaAsSb

203′ acts as an electron barrier and a hole well located between the pair of quantum wells. The fourth layer of this alternate embodiment, layer 204′, is similar to the second layer, layer 202′. The fourth layer, layer 204′, is one of a set of three materials. Layer 204′ may be Aluminum-Gallium-Arsenide (AlGaAs), Indium-Gallium-Phosphide (InGaP), or Indium-Gallium-Arsenide-Phosphide (InGaAsP). The fourth layer, layer 202′ acts an an electron well for electrons and a hole barrier for holes. The energy bands 601 and 602 illustrated in Figure 6 are with the fourth layer, layer 204′, being Indium-Gallium-Arsenide-Phosphide (InGaAsP). Layer 204′ is the second of two quantum wells forming the pair of quantum wells. The heterojunction layers 105′ and active region 106′ of the semiconductor laser may have additional sets of triad layers of InGaAsP/GaAsSb/InGaAsP; InGaP/GaAsSb/InGaP; or AlGaAs/GaAsSb/AlGaAs as the case may be. The final layer of the alternate embodiment is AlGaAs 205′, similar to AlGaAs 201′. AlGaAs 205′ also acts both as a cladding and barrier material for the quantum wells.

In the alternate embodiment illustrated by Figure 6, holes are confined to the narrower region of the GaAsSb 203′ than the electrons in layers 202′ and 204′ due to the conduction band offset, between the layer 203′ and the two adjacent layers 202′ and 204′, being smaller than kT or zero. The materials for layers 201′-205′ are of the appropriate composition to create a small or zero conduction band offset with the GaAsSb 203′. The electrons being confined to a larger volume have a reduced quantization energy. As a result, the material will emit photons at energies and wavelengths close to the energy gap of the GaAsSb 203′. By selecting a composition of materials for layers 201′-

205′ with a small enough energy gap, emission at wavelengths in the 1.2 to 1.5 μm region can be achieved.

The preferred embodiments of the present invention are thus described. The present invention has been described with relationship to VCSELs but is applicable to any type of semiconductor laser. While the present invention has been described in particular embodiments, the present invention should not be construed as limited by such embodiments, but rather construed according to the claims that follow below.

CLAIMS

What is claimed is:

1. A semiconductor laser for emitting photons at relatively long wavelengths, the semiconductor laser comprising:

a semiconductor substrate;

active layers to provide carrier confinement for lasing, the active layers including,

a first barrier layer,

at least one W quantum well structure having one layer coupled to the first barrier layer, the at least one W quantum well structure having an energy band reducing the energy gap between the conduction band and the valence band to emit photons at relatively long wavelengths, and

a second barrier layer coupled to another layer of the at least one W quantum well structure;

an optical confinement region coupled to the active layers and the semiconductor substrate, the optical confinement region to confine photons to an active region within the active layers; and

a first contact terminal and a second contact terminal, the first contact terminal coupled to a surface of the optical confinement region in such a way to allow emission of photons from a surface of the semiconductor laser, the second contact terminal coupled to the semiconductor substrate.

2. The semiconductor laser of claim 1 wherein,

the first and second barrier layers are Gallium-Arsenide and the at least one W quantum well structure includes the triad layers of Gallium-Arsenide-Nitride/Gallium-Arsenide-Antimonide/Gallium-Arsenide-Nitride.

3. The semiconductor laser of claim 2 wherein,

the Arsenide concentration varies as a percentage of (1-X) and the Nitride concentration varies as a percentage of X in each of Gallium-Arsenide-Nitride layers and the Arsenide concentration varies as a percentage of (1-Y) and the Antimony concentration varies as a percentage of Y in the Gallium-Arsenide-Antimonide layer.

4. The planar index guided vertical cavity surface emitting laser of claim 3 wherein,

the semiconductor laser is a vertical cavity surface emitting laser (VCSEL) and the photons are emitted from a surface of the VCSEL parallel with the active layers.

5. The semiconductor laser of claim 1 wherein,

the active layers further include another W quantum well structure similar to the at least one W quantum well structure where the second barrier layer is shared by the another W quantum well structure and the at least one W quantum well structure.

6. The semiconductor laser of claim 2 wherein,

the Gallium-Arsenide of the first and second barrier layers can range between ten and one hundred angstroms in thickness and the Gallium-Arsenide-Antimonide layer of the at least one W quantum well structure can range between ten and one hundred angstroms in thickness.

7. The semiconductor laser of claim 6 wherein, the Gallium-Arsenide-Nitride layers of the at least one W quantum well structure can range between ten and one hundred angstroms in thickness.

8. The semiconductor laser of claim 2 wherein, the Gallium-Arsenide of the first and second barrier layers is approximately twenty five angstroms in thickness and the Gallium-Arsenide-Antimonide layer of the at least one W quantum well structure is approximately fifty angstroms in thickness.

9. The semiconductor laser of claim 8 wherein, the Gallium-Arsenide-Nitride layers of the at least one W quantum well structure are approximately twenty five angstroms in thickness.

10. The semiconductor laser of claim 1 wherein, the first and second barrier layers are Aluminum-Gallium-Arsenide and the at least one W quantum well structure includes a central layer of the triad layers of the at least one W quantum well structure of Gallium-Arsenide-Antimonide.

11. The semiconductor laser of claim 10 wherein, the two layers sandwiching the central layer are a material of the set of Aluminum-Gallium-Arsenide, Indium-Gallium-Phosphide, and Indium-Gallium-Arsenide-Phosphide.

12. A method of fabricating semiconductor lasers on Gallium-Arsenide substrates where the wavelength of photon emission is longer than ordinarily achievable using Gallium-Arsenide, the method comprising:

providing a Gallium-Arsenide substrate;

providing a region of optical confinement; and

providing a plurality of heterojunction layers where an active region of the heterojunction layers overlaps the region of optical confinement, the plurality of heterojunction layers forming a quantum well material system in which free electrons and holes for recombining into photons are confined to adjacent layers of materials due to a type II energy band offset formed by the adjacent layers of materials.

13. The method of claim 12 wherein,

one of the adjacent layers is Gallium-Arsenide-Antimonide in which the holes are confined.

14. The method of claim 13 wherein,

the other one of the adjacent layers is Gallium-Arsenide-Nitride in which the electrons are confined.

15. The method of claim 14 wherein,

the thicknesses and concentration of semiconductor laser materials are selected such that the wavelength of photon emission during lasing is in the range between 1.3 micron to 1.7 micron.

16. The method of claim 14 wherein,

the thicknesses and concentration of semiconductor laser materials are selected such that the wavelength of photon emission during lasing is in the range between 1.3 micron to 1.55 micron.

17. The method of claim 12 wherein,

the heterojunction layers are strain compensated by using alternating layers of a tensile strained layer and a compressive strained layer to further increase the wavelength of photon emission when the semiconductor laser is lasing.

18. The method of claim 17 wherein,
one of the adjacent layers is Gallium-Arsenide-Antimonide in which the holes are confined.

19. The method of claim 18 wherein,
the other one of the adjacent layers is Gallium-Arsenide-Nitride in which the electrons are confined.

20. The method of claim 19 wherein,
each of the adjacent layers is sufficiently thin such that quantum effects become important and each layer forms a quantum well.

21. The method of claim 20 wherein,
a pair of quantum wells formed of two sets of adjacent layers is a W quantum well structure.

22. An active area for a semiconductor laser for lasing at wavelengths greater than a Gallium-Arsenide active area, the active area comprising:

at least one W quantum well materials system, the at least one W quantum well materials system including,

a first barrier layer,

a first quantum well layer coupled to the first barrier layer, the first quantum well layer having an energy band reducing the energy gap between the conduction band and the valence band to emit photons at relatively long wavelengths, a second barrier layer coupled to the first quantum well layer,

a second quantum well layer coupled to the second barrier layer, the second quantum well layer having an energy band reducing the energy gap between the conduction band and the valence band to emit photons at relatively long wavelengths, and

a third barrier layer coupled to the second quantum well layer.

23. The active area of claim 22 for a semiconductor laser wherein,

the first and third barrier layers are Gallium-Arsenide, the first and second quantum well layers are Gallium-Arsenide-Nitride and the second barrier layer is Gallium-Arsenide-Antimonide.

24. The active area of claim 22 for a semiconductor laser wherein,

the first and third barrier layers are Aluminum-Gallium-Arsenide and the second barrier layer is Gallium-Arsenide-Antimonide.

25. The semiconductor laser of claim 24 wherein, the two quantum well layers sandwiching the second barrier layer are a material of the set of Aluminum-Gallium-Arsenide, Indium-Gallium-Phosphide, and Indium-Gallium-Arsenide-Phosphide.

26. The semiconductor laser of claim 22 further comprising:

a third quantum well layer coupled to the third barrier layer, the third quantum well layer having an energy band reducing the energy gap between the conduction band and the valence band to emit photons at relatively long wavelengths, and

a fourth barrier layer coupled to the third quantum well layer.

27. The active area of claim 26 for a semiconductor laser wherein,

the first and fourth barrier layers are Gallium-Arsenide, the first, second and third quantum well layers are Gallium-Arsenide-Nitride and the second and third barrier layer are Gallium-Arsenide-Antimonide.

28. A method of lasing at relatively long wavelengths in a semiconductor laser, the method comprising:

providing a semiconductor laser having a W quantum well materials system;

providing a forward bias across the terminals of the semiconductor laser; and

providing a threshold current through the terminals of the semiconductor laser sufficient to inject carriers into an active region to have holes and electrons in the W quantum well materials system recombine and emit photons.

29. The method of claim 28 of lasing at relatively long wavelengths in a semiconductor laser wherein, the W quantum well materials system includes, a first quantum well layer, the first quantum well layer having an energy band reducing the energy gap between the conduction band and the valence band to emit photons at relatively long wavelengths, a central barrier layer coupled to the first quantum well layer, and a second

quantum well layer coupled to the second barrier layer, the second quantum well layer having an energy band reducing the energy gap between the conduction band and the valence band to emit photons at relatively long wavelengths;

and wherein the W quantum well materials system is sandwiched by two outer barrier layers coupled to the W quantum well materials system.

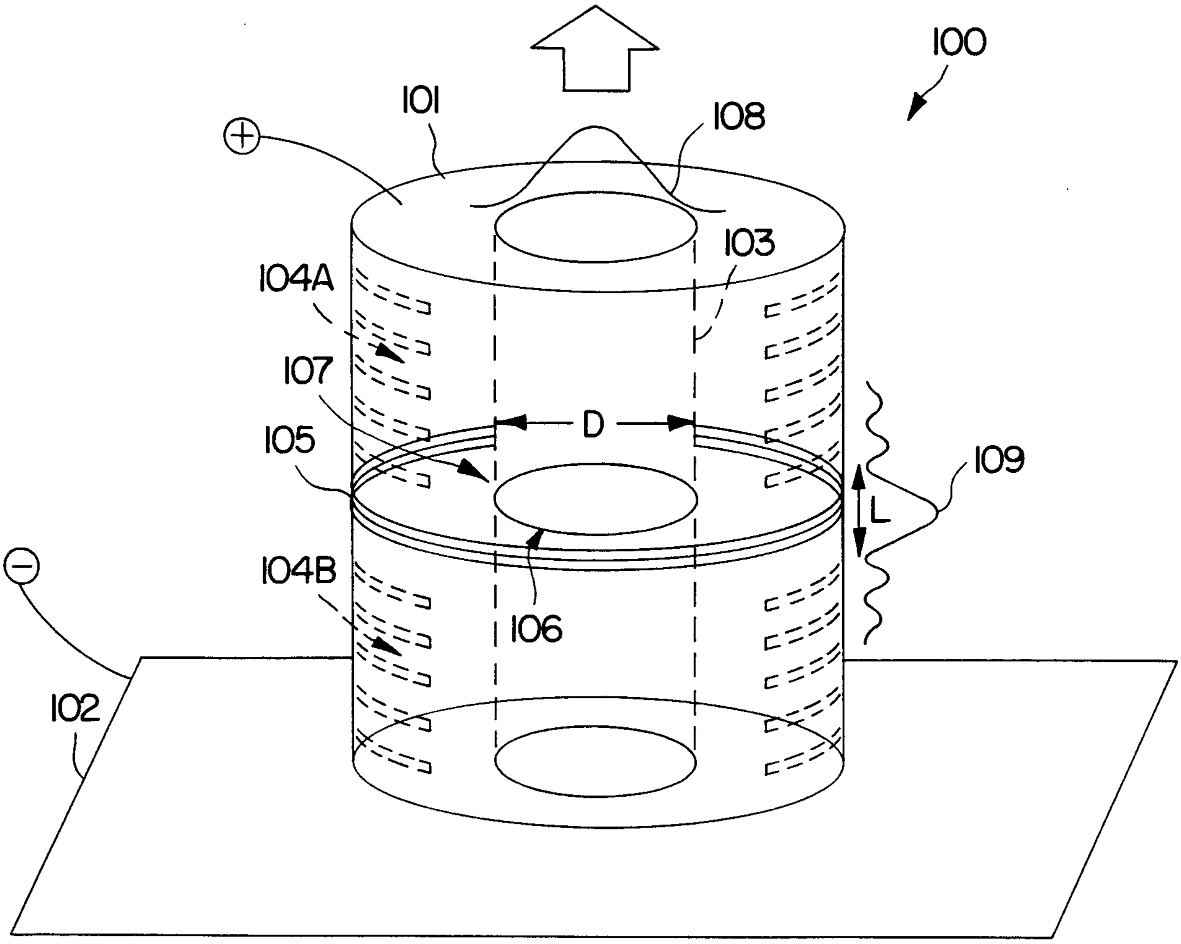

FIG. 1
PRIOR ART

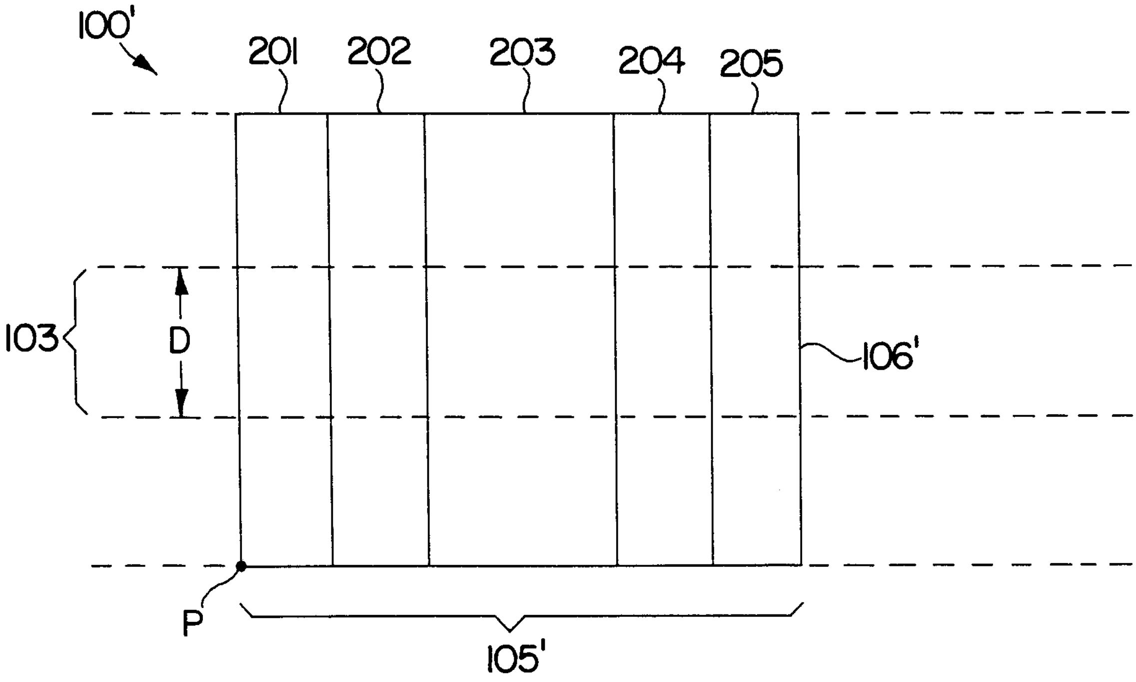
100'
201
202
203
204
205
103
D
106'
P
105'

FIG. 2A

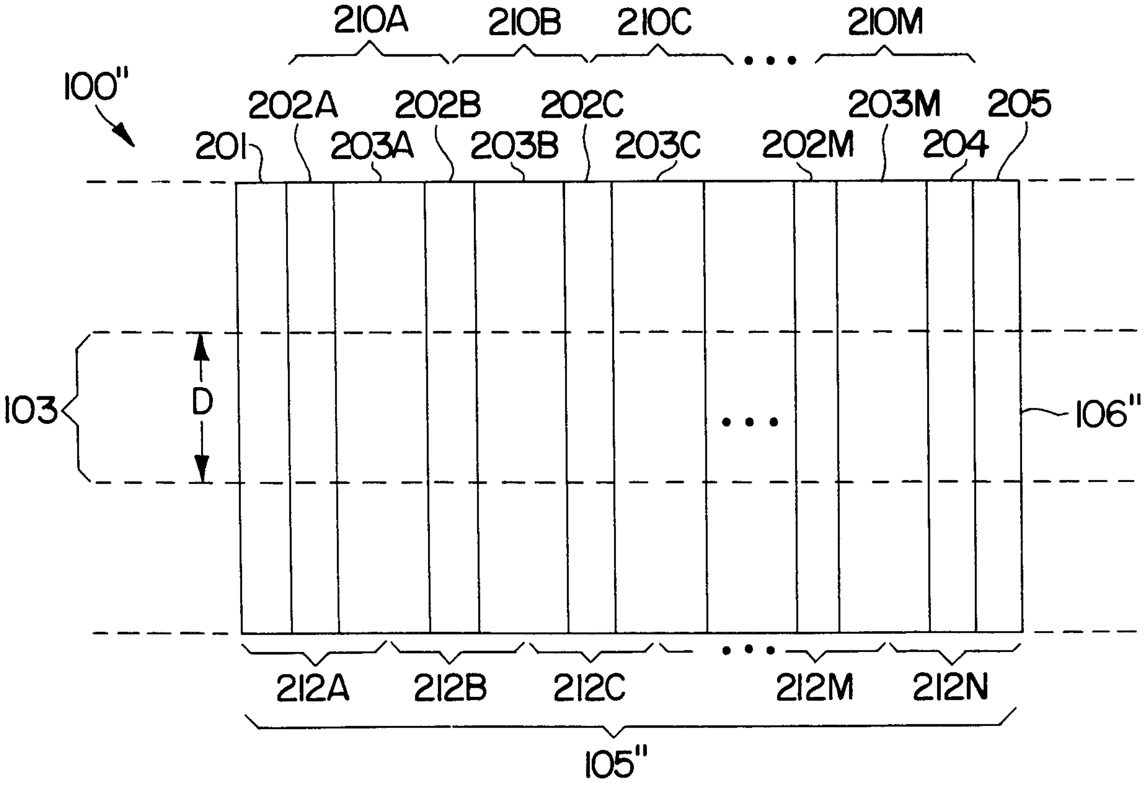
210A
210B
210C
210M
100"
202A
202B
202C
203M
205
201
203A
203B
203C
202M
204
103
D
106"
212A
212B
212C
212M
212N
105"

FIG. 2B

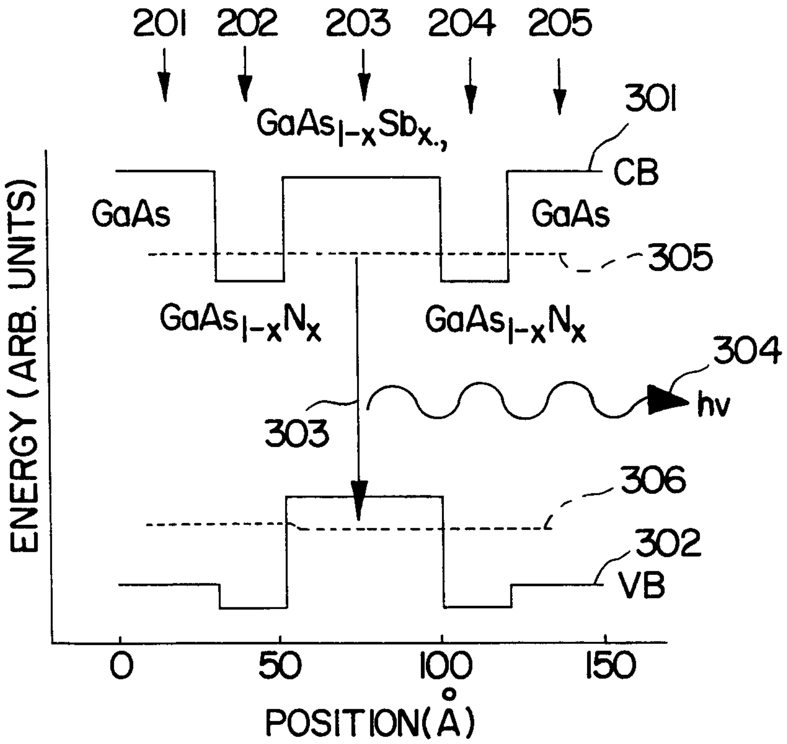
201
202
203
204
205
$GaAs_{1-x}Sb_{x}$.,
301
CB
GaAs
GaAs
305
$GaAs_{1-x}N_{x}$
$GaAs_{1-x}N_{x}$
304
hv
303
306
302
VB
ENERGY (ARB. UNITS)
0
50
100
150
POSITION(Å)

FIG.3

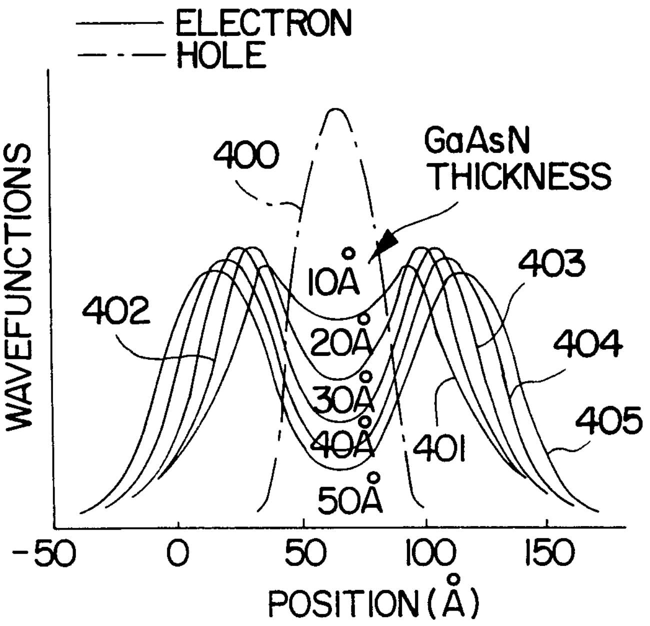
ELECTRON
HOLE
400
GaAsN
THICKNESS
10Å
20Å
30Å
40Å
50Å
402
403
404
401
405
WAVEFUNCTIONS
-50
0
50
100
150
POSITION (Å)

FIG. 4

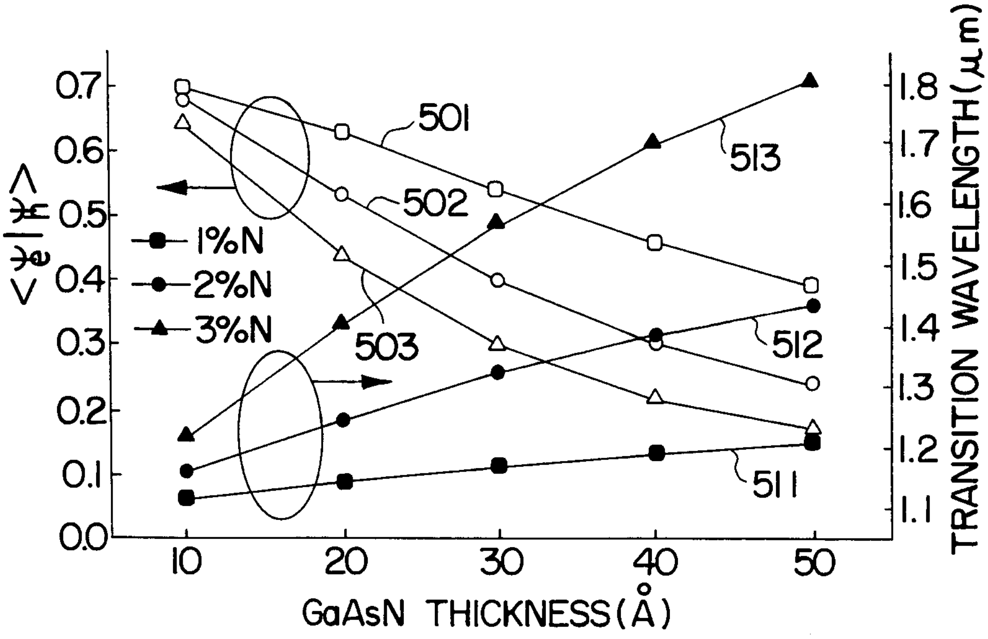
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
<ψe|ψh>
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
TRANSITION WAVELENGTH (μm)
1%N
2%N
3%N
501
502
503
511
512
513
10
20
30
40
50
GaAsN THICKNESS (Å)

FIG. 5

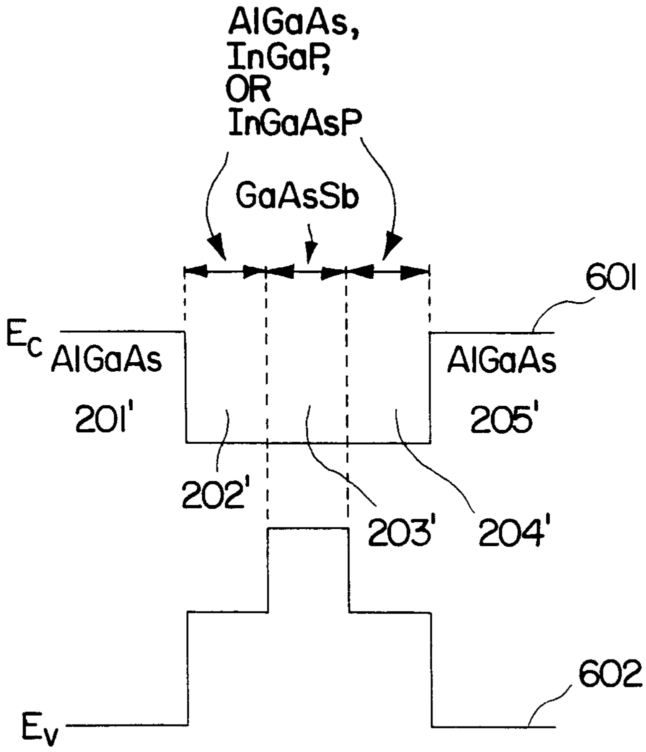
AlGaAs, InGaP, OR InGaAsP
GaAsSb
601
Ec
AlGaAs
201'
AlGaAs
205'
202'
203'
204'
602
Ev

FIG. 6A

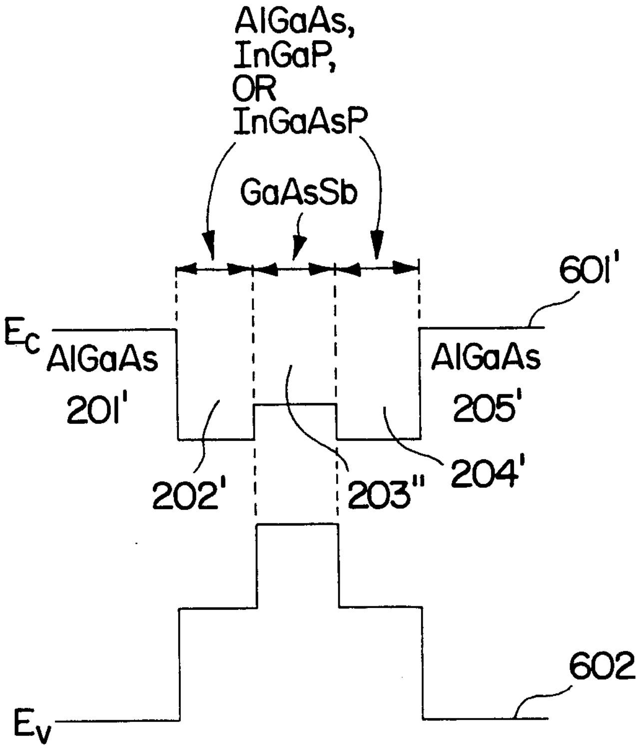
AlGaAs,
InGaP,
OR
InGaAsP
GaAsSb
601'
E_C
AlGaAs
201'
AlGaAs
205'
202'
203''
204'
602
E_V

FIG. 6B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/14332

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H01S 5/183, 5/34
US CL : 372/45, 96
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 372/45, 96

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EAST (APS)
search terms: W quantun well, VCSEL, Galium-Arsenide-Antimonide

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	BEWLEY W. W. et al High-temperature continuous-wave 3-6.1 micron "W" lasers with diamond-pressure-bond heat sinking, APPLIED PHYSICS LETTERS Voume 74, Number 8, 22 February 1999, entire document.	1-29

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier document published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search 08 NOVEMBER 2000	Date of mailing of the international search report 28 NOV 2000
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