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(54) **TYPE II QUANTUM WELL OPTOELECTRONIC DEVICES**

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(52) **U.S. Cl.** **257/14**; 257/103; 372/44
(58) **Field of Search** 257/14

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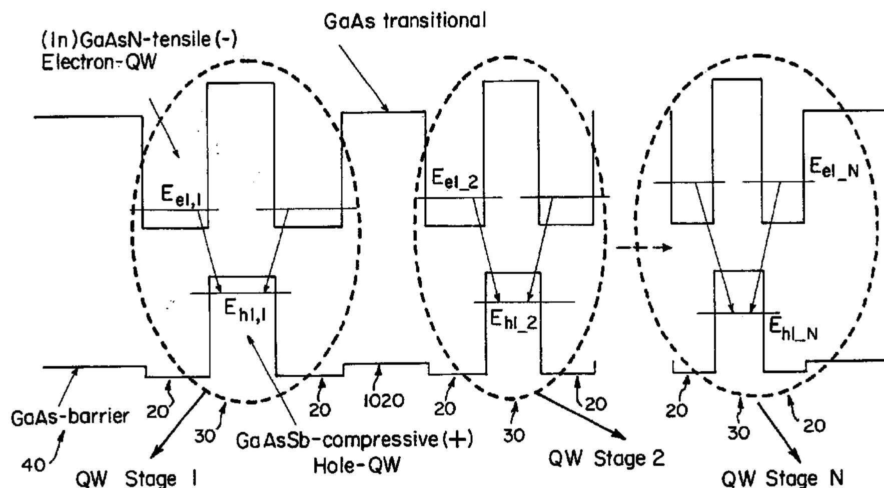
(57) **ABSTRACT**

Semiconductor optoelectronic devices such as diode lasers are formed on GaAs with an active region with a GaAsN electron quantum well layer and a GaAsSb hole quantum well layer which form a type II quantum well. The active region may be incorporated in various devices to provide light emission at relatively long wavelengths, including light emitting diodes, amplifiers, surface emitting lasers and edge-emitting lasers.

33 Claims, 12 Drawing Sheets



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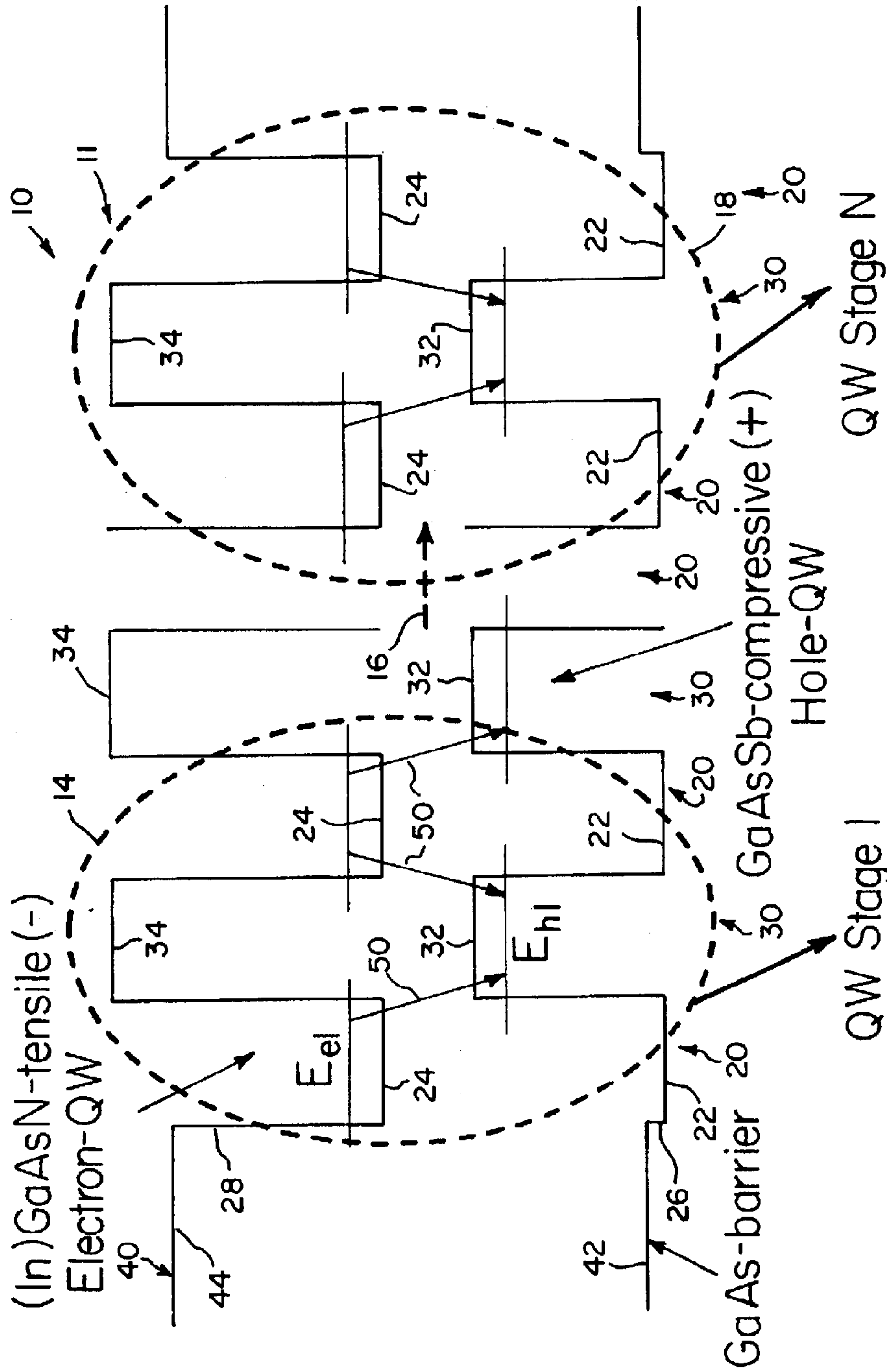


FIG. 1

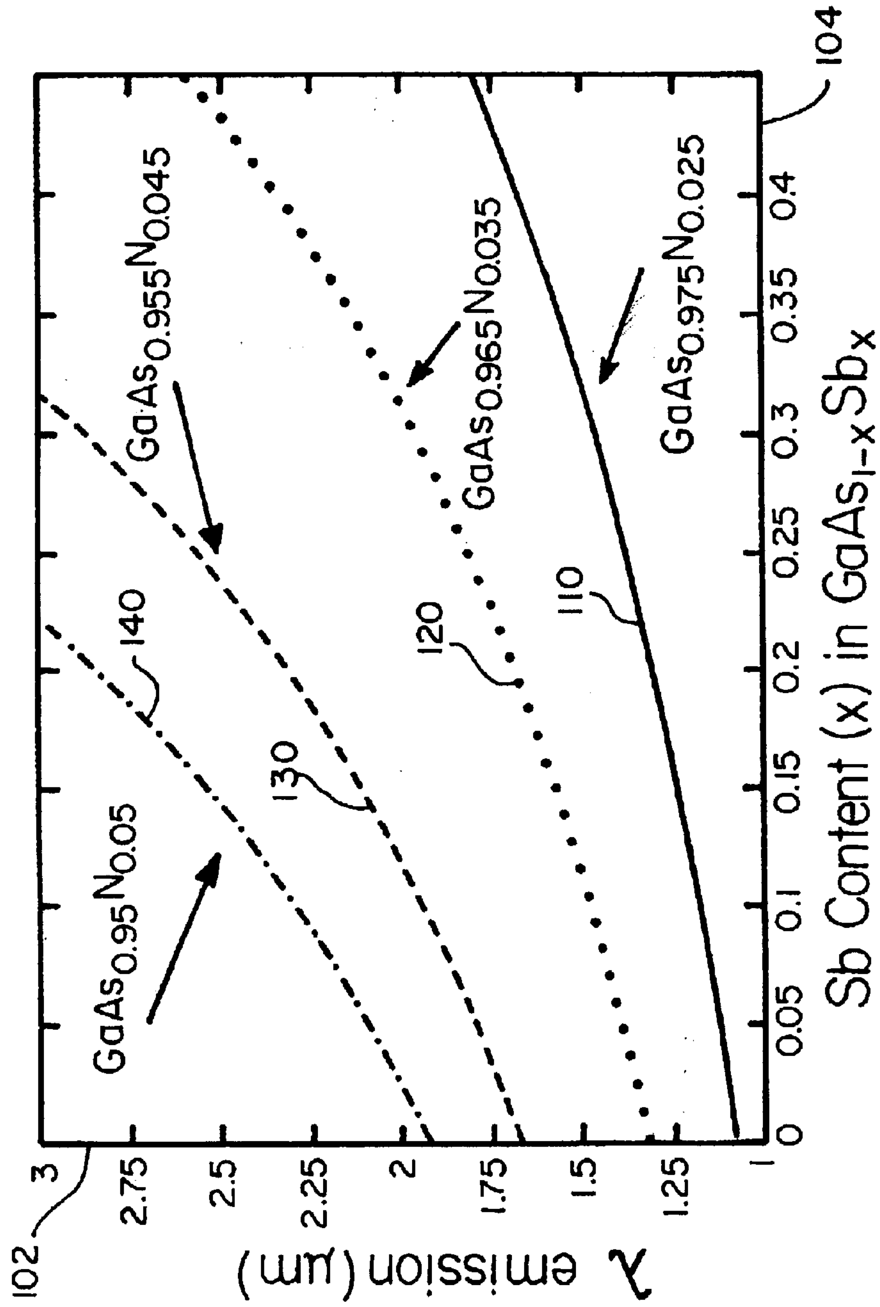


FIG. 2

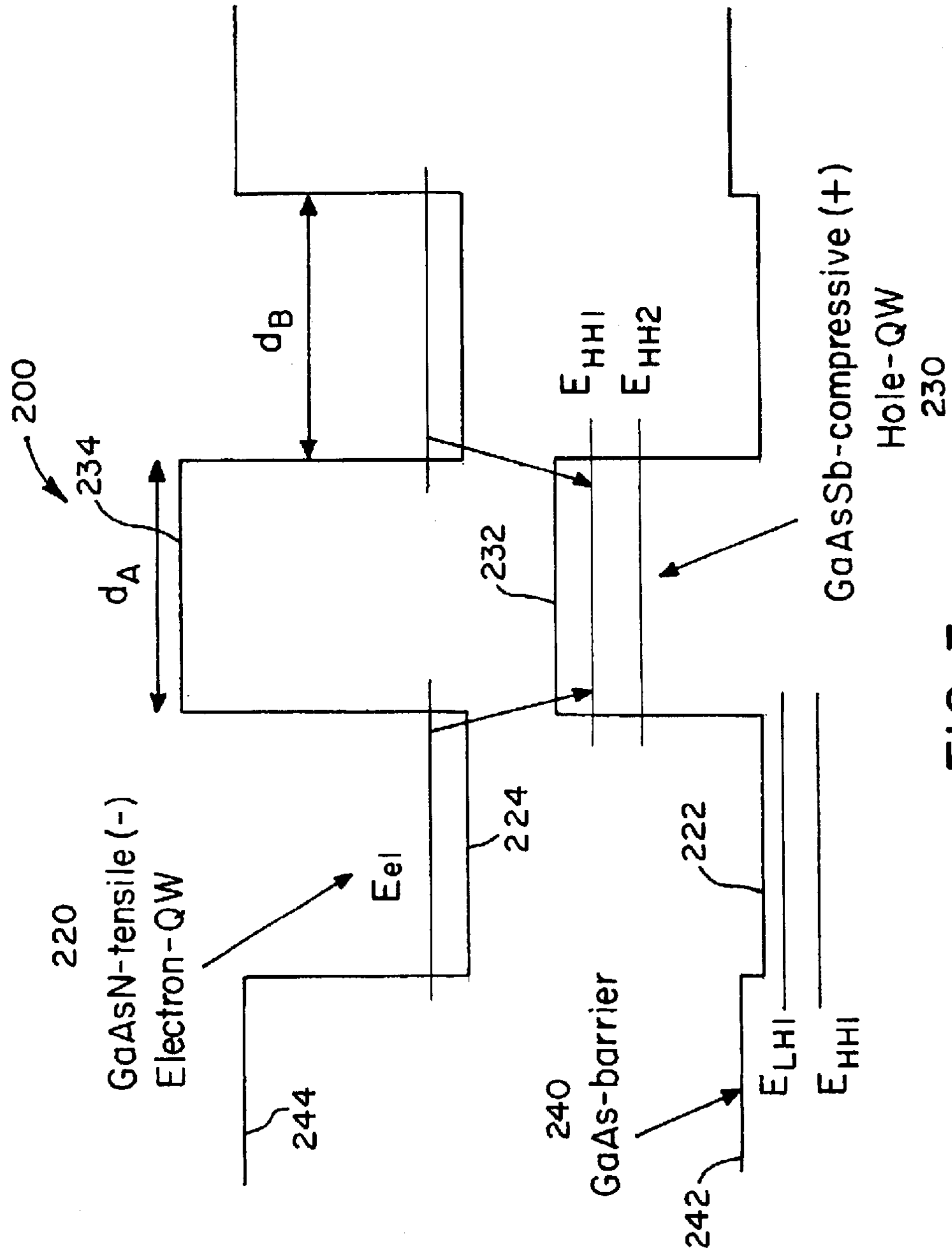
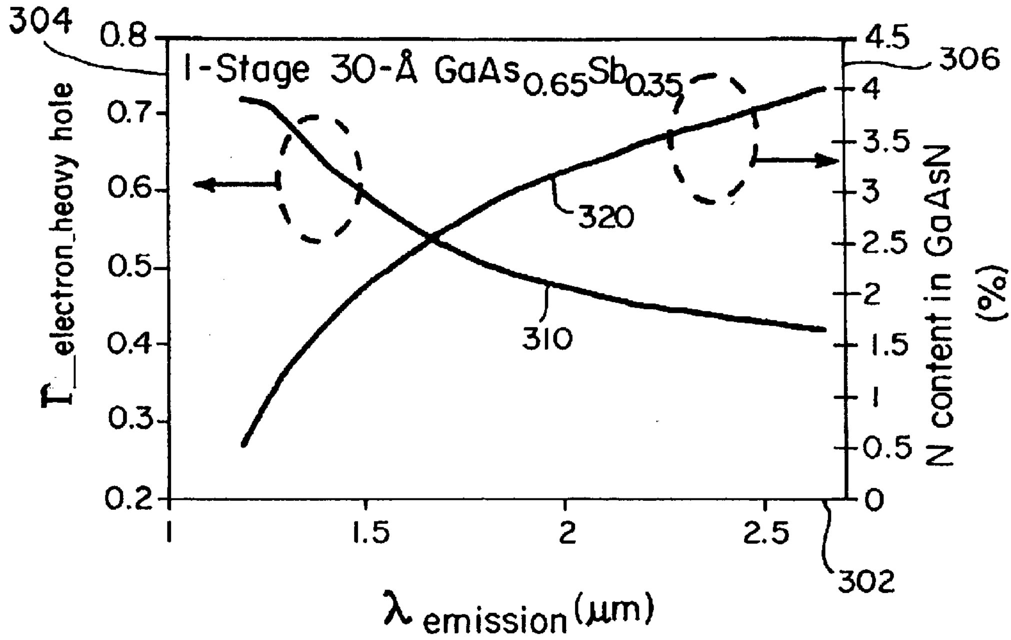


FIG. 3



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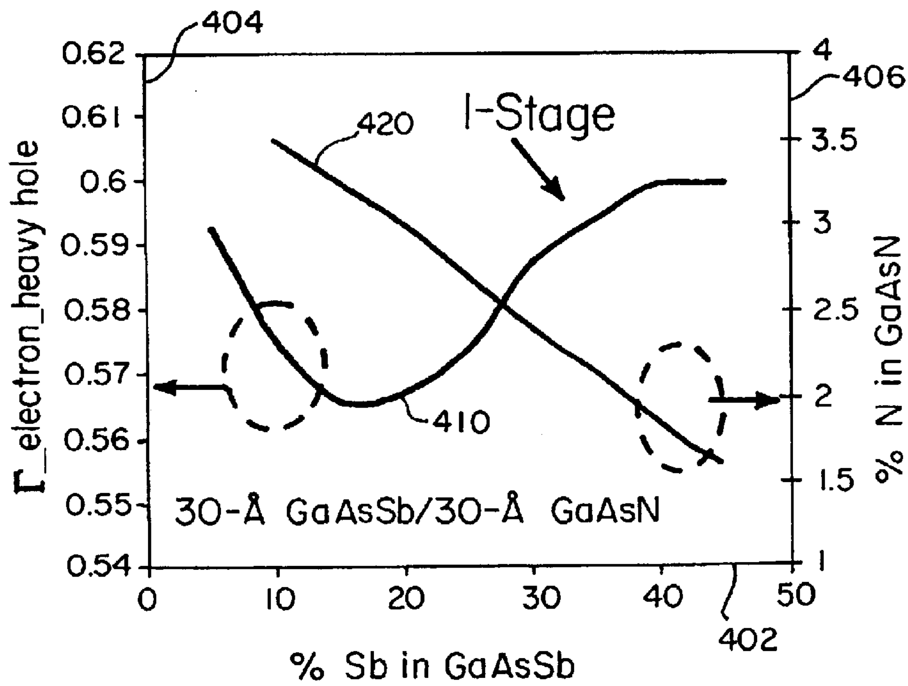

FIG. 5

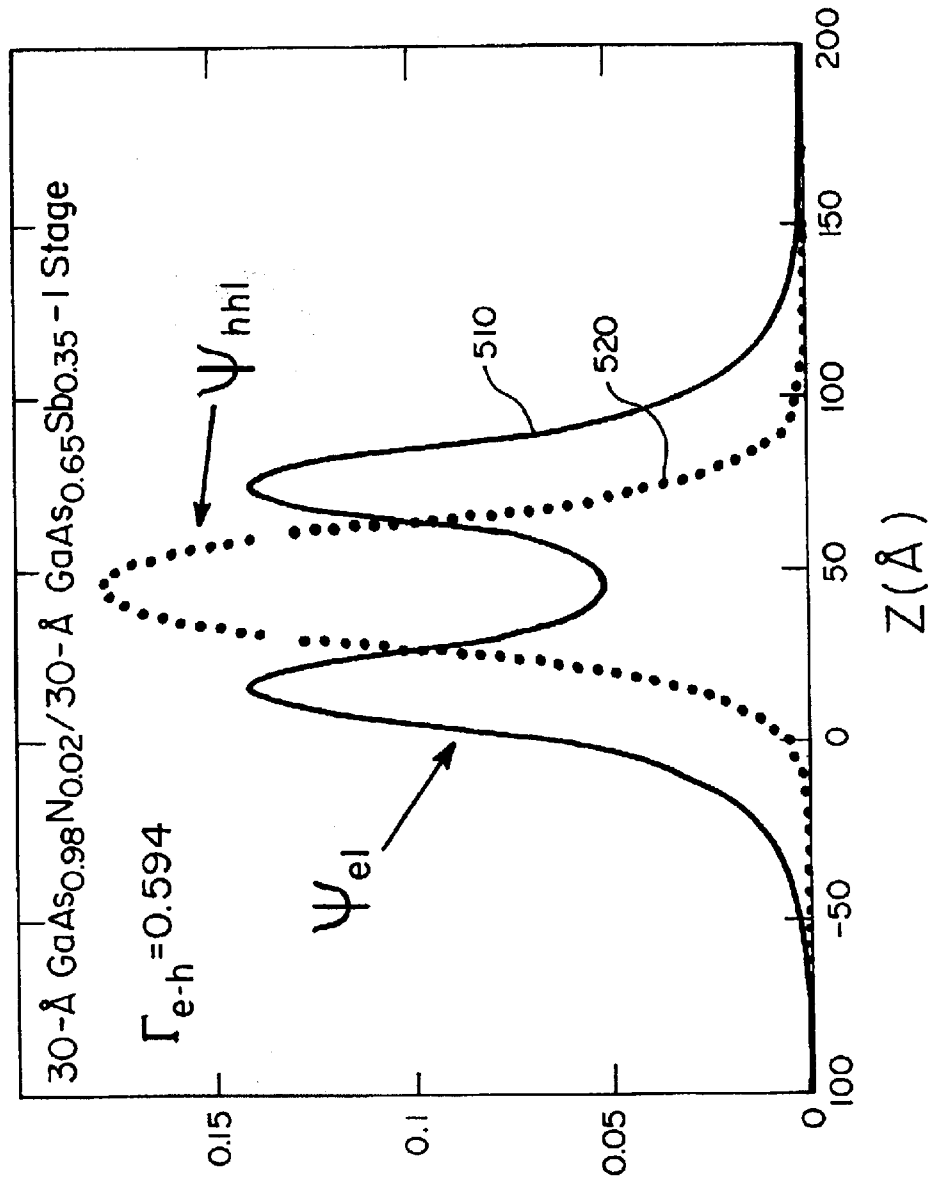

FIG. 6

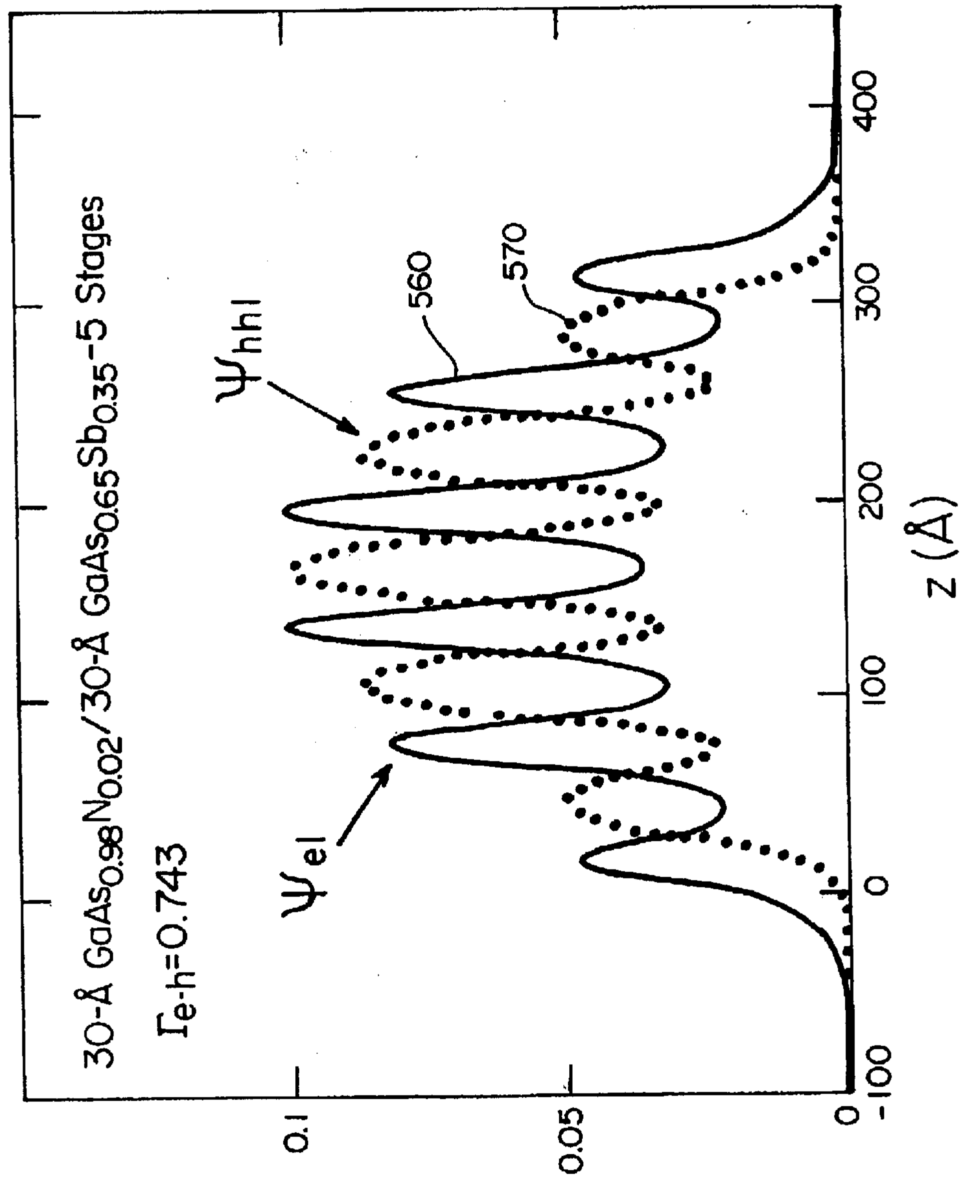

FIG. 7

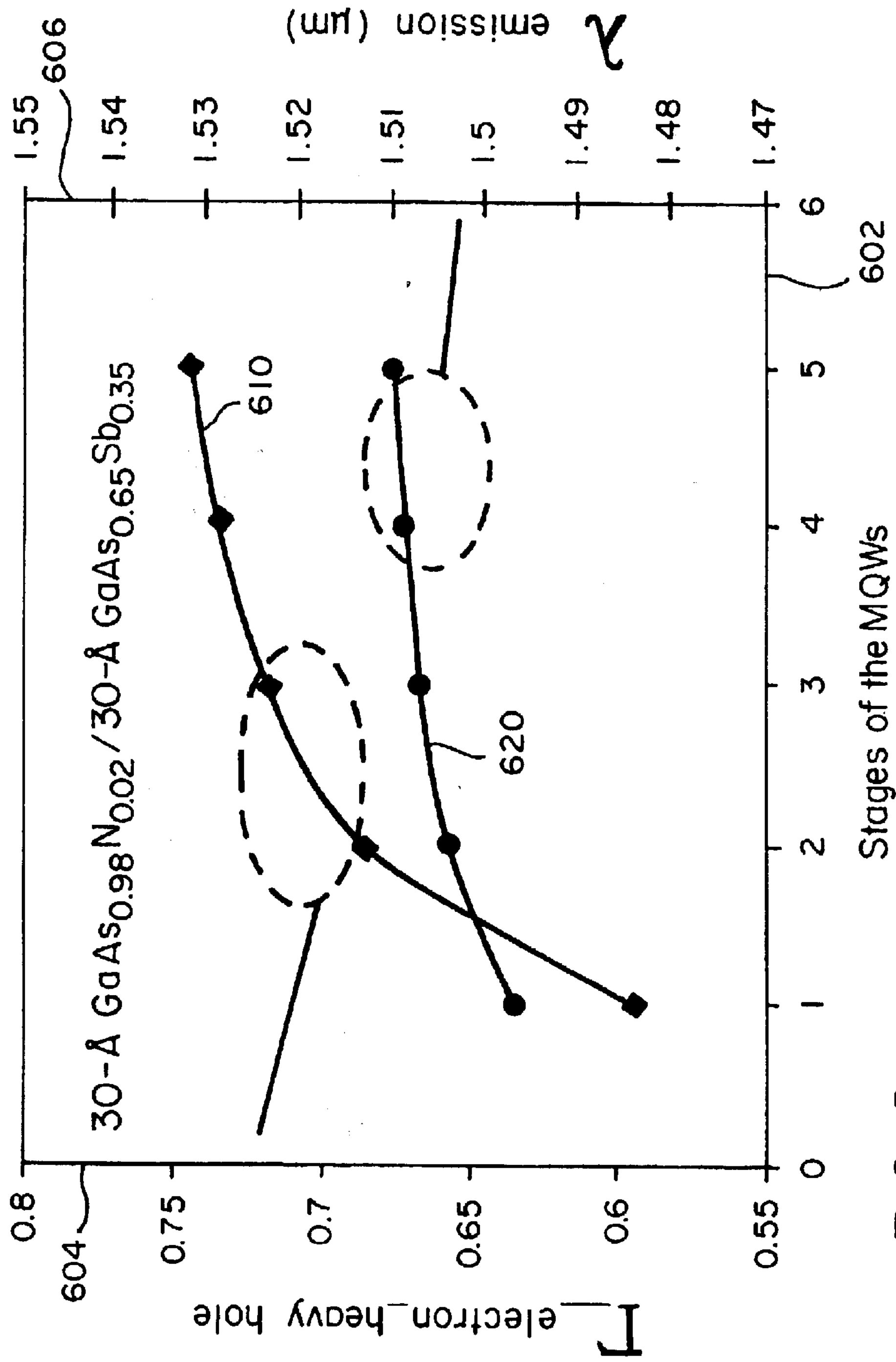

FIG. 8

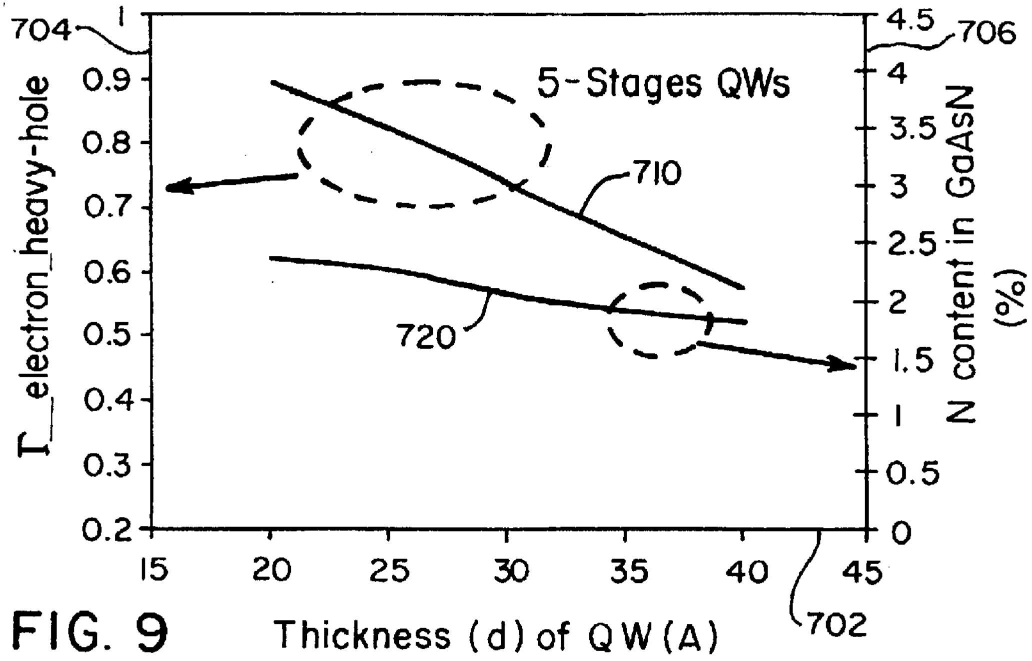

FIG. 9

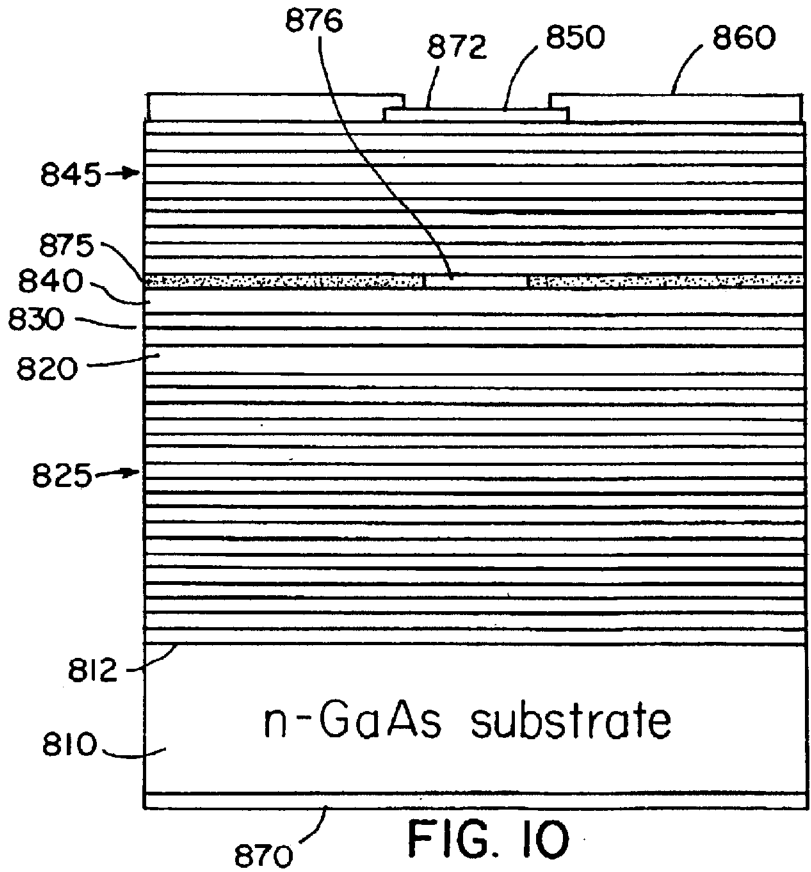

FIG. 10

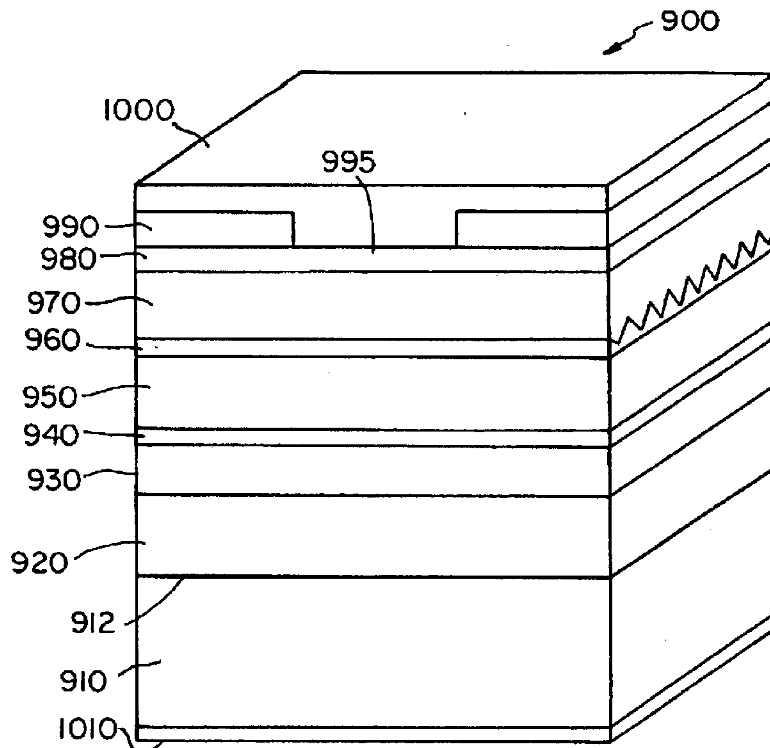

FIG. 11

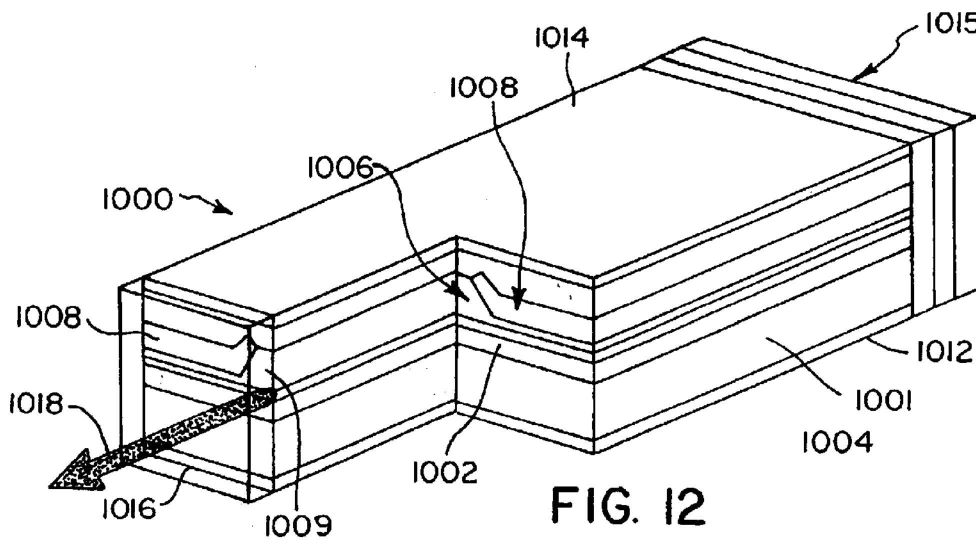

FIG. 12

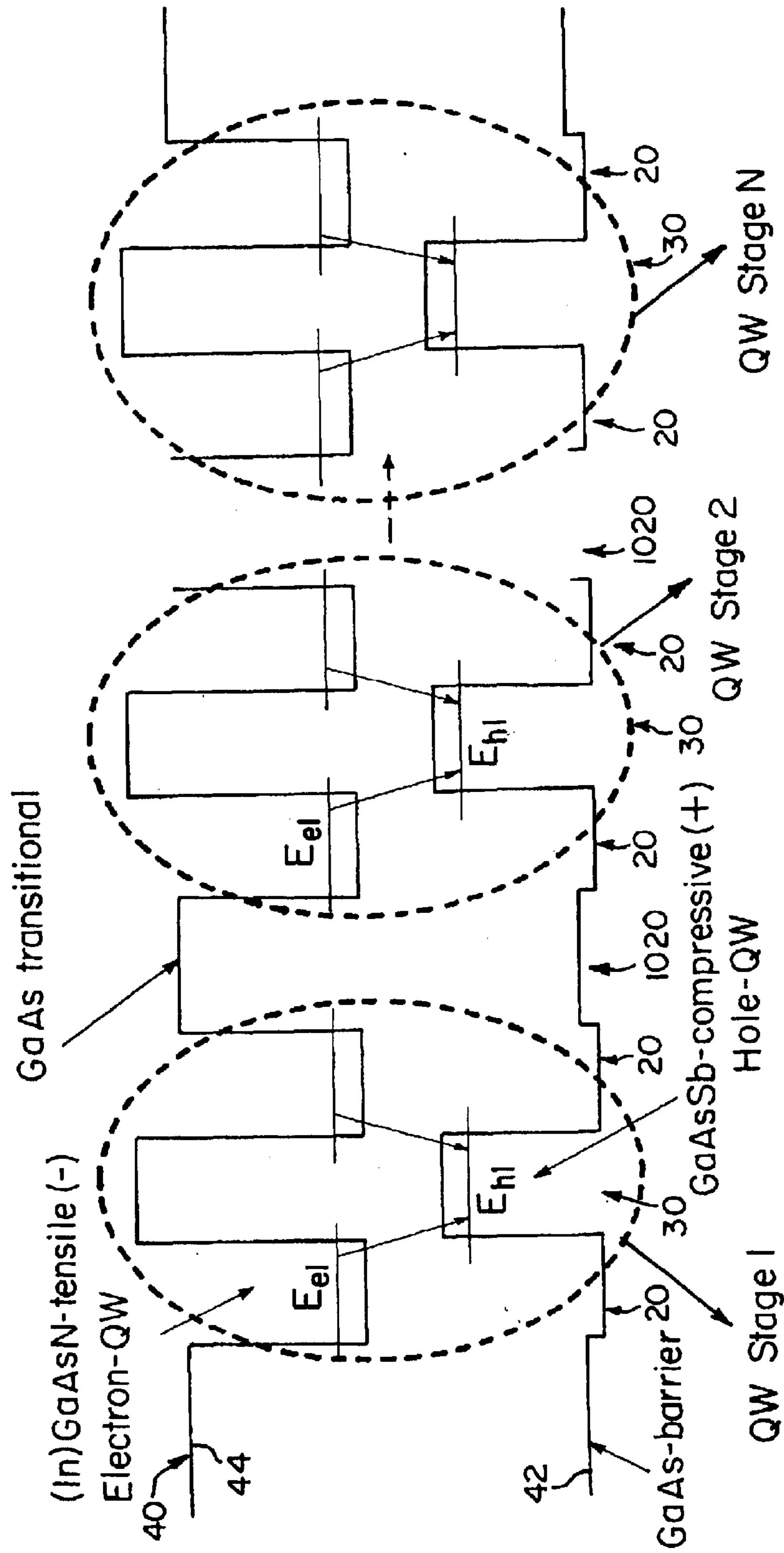

FIG. 13

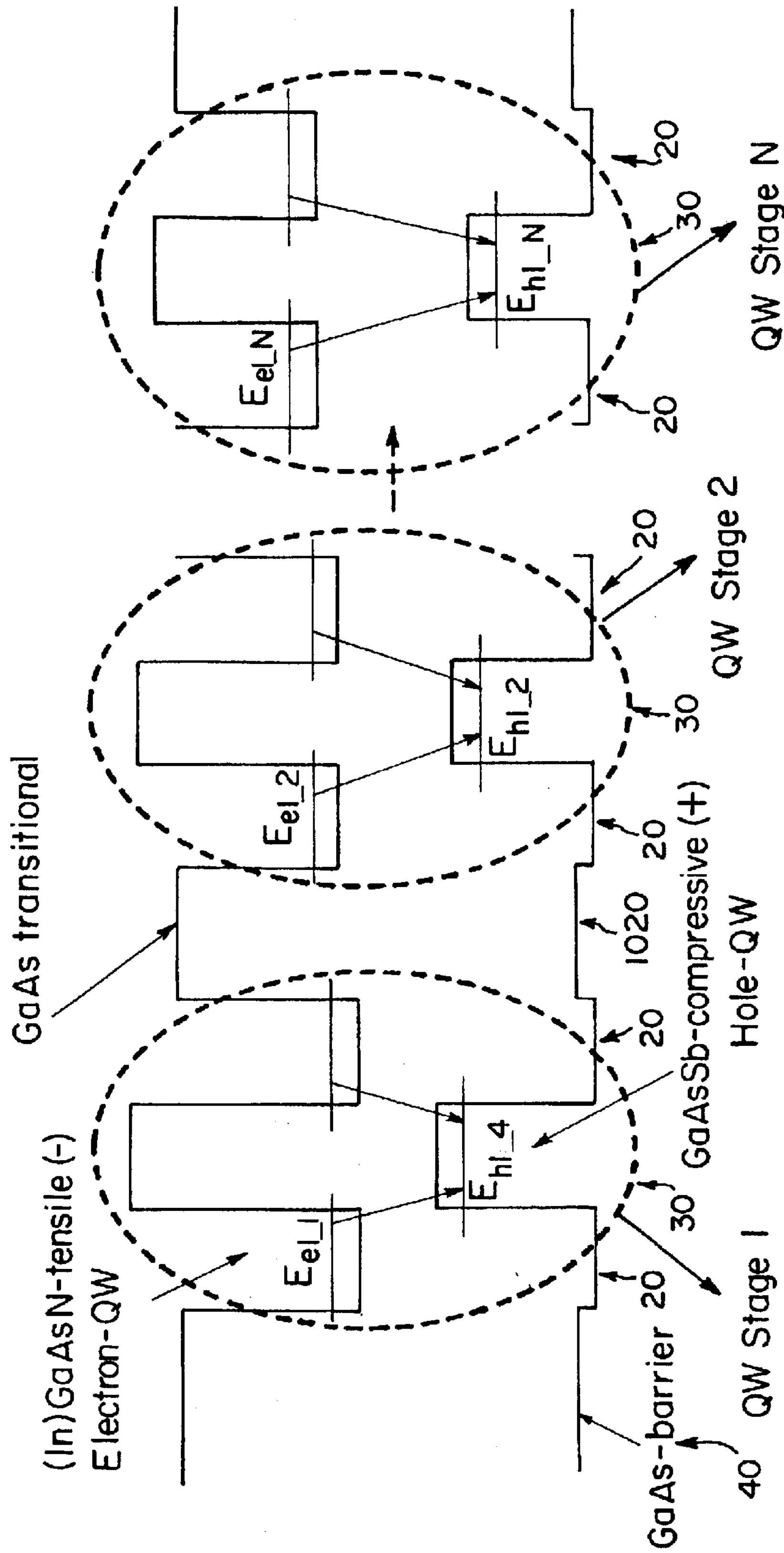

FIG. 14

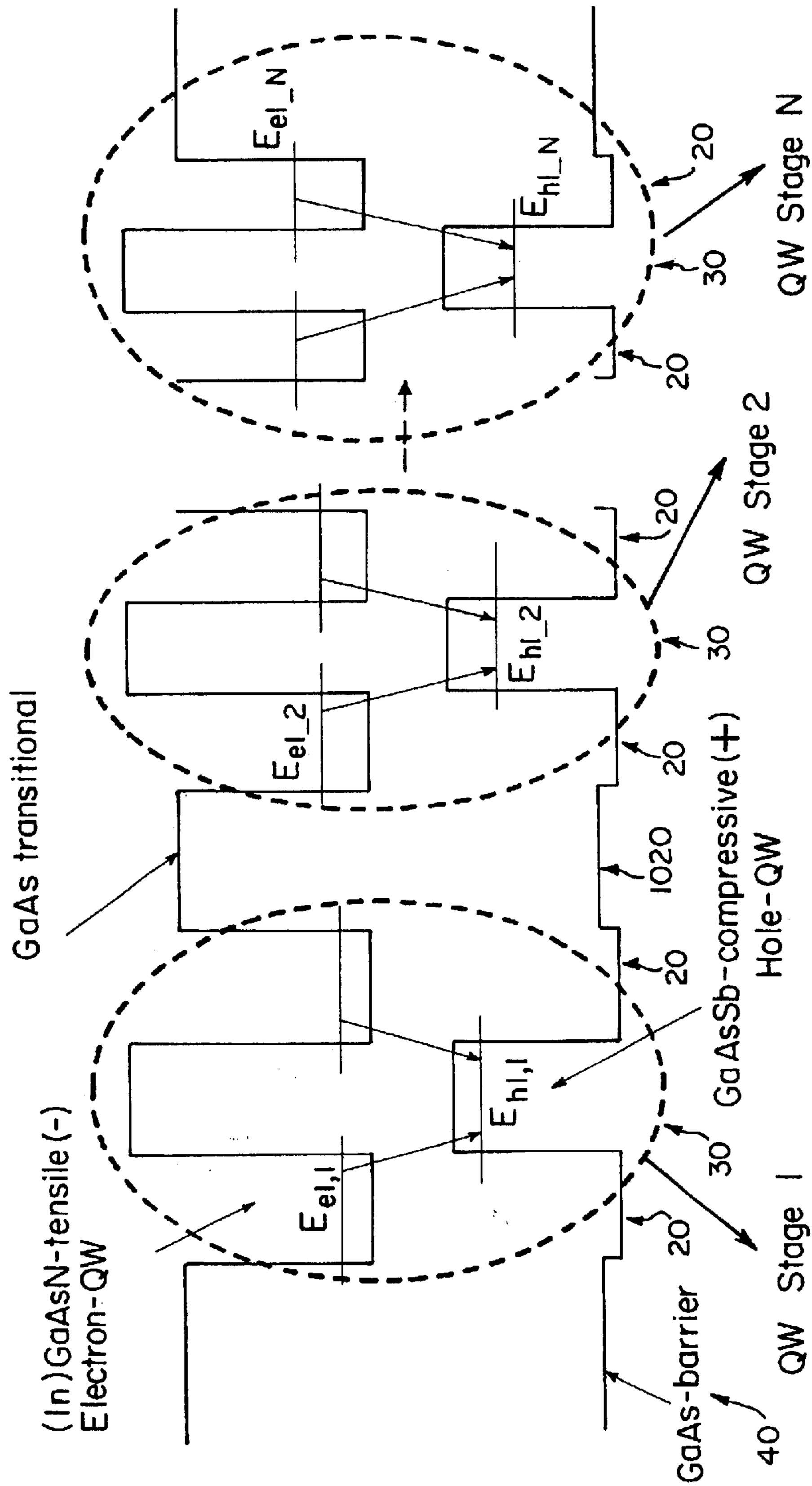

FIG. 15

TYPE II QUANTUM WELL OPTOELECTRONIC DEVICES

STATEMENT OF GOVERNMENT RIGHTS

This invention was made with United States Government support awarded by the following agency: NSF 9734283. The United States has certain rights in this invention.

FIELD OF THE INVENTION

The present invention relates generally to the field of optoelectronic devices such as light emitting diodes and semiconductor diode lasers and more specifically to the field of type II quantum well devices.

BACKGROUND OF THE INVENTION

Fiber optic transmission of data signals across large distances is presently accomplished using a variety of laser transmitters, which are generally designed to operate in three primary wavelengths, e.g., 850 nanometers, 1.3 μm, and 1.55 μm. For a predetermined bandwidth, increasing the wavelength of light emitted from a laser transmitter acts to increase the distance that data and information may travel without requiring amplification. For example, in a system having a 10 gigabyte per second bandwidth, use of an 850 nanometer wavelength transmitter allows signals to be transmitted between approximately 50 to 100 meters without amplification, while the use of a transmitter in the 1.55 μm regime allows transmission of signals up to approximately 2000 kilometers without amplification. Amplification of these signals (e.g., using an erbium amplifier) allows propagation of such signals even greater distances.

Long-haul fiber optic transmissions currently utilize 1.55 micrometer distributed feedback (DFB) edge emitting lasers as transmitters. Such DFB lasers are relatively expensive, and vertical cavity surface emitting lasers (VCSELs) potentially offer a lower-cost alternative to DFB edge emitting lasers.

A number of issues are presented by previous attempts to produce relatively low cost, manufacturable VCSEL lasers having emission wavelengths in the 1.55 μm. For example, InP-based 1.5 micrometer VCSELs conventionally use wafer-bonding distributed Bragg reflectors (DBRs), metamorphic DBRs, or Sb-based DBRs. Such VCSELs require relatively sophisticated and challenging fabrication processes. Lasing performance of such VCSELs is also generally inferior to InP-based edge-emitting lasers.

Conventional active regions for 1.55 μm lasers (e.g., edge-emitting lasers for use as laser pumps for Raman fiber amplifiers) are based on InGaAs or InGaAsP multiple quantum wells (MQWs) on InP substrates. Such lasers are inherently temperature-sensitive, which may not be suitable for a number of applications. It is believed that the temperature sensitivity results from several factors, including Auger recombination, carrier leakage processes, intervalence band absorption (IVBA), and temperature dependency of the material gain.

Difficulties in forming high quality DBRs on InP substrates and the temperature sensitivity of resulting activation regions has led to research in extending emission wavelengths on GaAs substrates (e.g., using highly-strained InGaAsN(Sb) quantum wells (QWs) and InGaAs—GaAsSb type II QWs. This research has not produced high-performance laser operation at 1.55 μm.

Thus, it would be advantageous to be able to provide a laser that exhibits high performance laser operation in the 1.55 μm regime using a GaAs substrate, and which may be produced relatively simply and inexpensively in comparison with conventional 1.55 μm lasers. It would be particularly advantageous to provide these characteristics in a VCSEL laser.

SUMMARY OF THE INVENTION

In accordance with the present invention, GaAs based optoelectronic devices have an active region that includes electron quantum well layers of GaAsN or InGaAsN and a hole layer quantum well of GaAsSb with a type II structure. The GaAsN or InGaAsN electron quantum well layer is preferably in tensile strain and the GaAsSb hole quantum well layer is preferably in compressive strain to provide light generation at desired wavelengths. Light can be generated at relatively long wavelengths, e.g., 1.3 μm or higher. A GaAs barrier layer is preferably formed adjacent to the GaAsN or InGaAsN layer.

In the devices of the invention, a multilayer semiconductor structure incorporating this active region layer is preferably epitaxially deposited on a substrate of GaAs. The thicknesses of the quantum well layers may each preferably be at least about 20 Å and less than about 50 Å. The quantum well layers can be selected to provide light emission at relatively long wavelengths, e.g., in the range of 1.3 μm to 3.0 μm.

The device preferably includes multiple quantum wells. Such a multiple-stage quantum well device includes a substrate comprising GaAs and a GaAs barrier layer, and multiple quantum well stages each of which includes GaAsN or InGaAsN electron quantum well layers and a GaAsSb hole quantum layer, each having appropriate strain for the desired wavelength of light emission.

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** is a schematic energy band diagram for a multiple-stage type II quantum well device in accordance with the invention.

FIG. **2** is a graph showing the calculated emission wavelength of a GaAsN—GaAsSb—GaAs type II quantum well with 40 Å individual well thicknesses for various Sb and N content, with strain effect and maximum quantum confinement effect.

FIG. **3** is a schematic energy band diagram for a single-stage type II quantum well device showing the respective hole energy band edge for GaAsN and GaAsSb.

FIG. **4** are graphs showing the relationship between wavefunctions overlap and emission wavelength for an exemplary single-stage 30 Å/30 Å/30 Å GaAsN/$GaAs_{0.05}Sb_{0.35}$/GaAsN quantum well device and the relationship between nitrogen content in the GaAsN layers and the emission wavelength.

FIG. **5** are graphs showing the relationship between nitrogen and antimony content in the GaAsN and GaAsSb layers of a single-stage quantum well device to achieve an emission wavelength of approximately 1.55 μm and the relationship between wavefunctions overlap and antimony content in the GaAsSb layer.

FIG. **6** are graphs showing the wavefunctions overlap for electron and heavy-hole wavefunctions of a single-stage quantum well device.

FIG. **7** are graphs showing the wavefunctions overlap for electron and heavy-hole wavefunctions of a 5-stage quantum well device.

FIG. **8** are graphs showing the relationship between wavefunctions overlap and the number of stages provided in a device having $GaAs_{0.58}N_{0.02}/GaAs_{0.65}Sb_{0.35}/GaAs_{0.98}N_{0.02}$ quantum wells and the relationship between emission wavelength and the number of stages in such a device.

FIG. **9** are graphs showing the relationship between wavefunctions overlap and thickness of quantum well layers in a 5-stage $GaAs_{0.98}N_{0.02}/GaAS_{0.65}Sb_{0.35}/GaAs_{0.98}N_{0.02}$ quantum well device and also showing the relationship between nitrogen content and the thickness of quantum well layers ($d=d_A=d_B$) for an emission wavelength of approximately 1.5 μm.

FIG. **10** is a schematic cross-sectional diagram of a vertical cavity surface emitting laser in accordance with an exemplary embodiment of the invention.

FIG. **11** is a schematic diagram of an edge-emitting laser in accordance with another exemplary embodiment of the invention.

FIG. **12** is a schematic diagram of another embodiment of an edge-emitting laser in accordance with the invention.

FIG. **13** is a schematic energy band diagram for a multiple stage type II quantum well device having GaAs transitional barriers.

FIG. **14** is a schematic energy band diagram for a multiple stage type II quantum well device having a chirped or graded change in composition of the quantum wells transversely through the set of quantum wells.

FIG. **15** is a schematic energy band diagram for a multiple stage type II quantum well device having a chirped or graded change in quantum well dimensions transversely through the set of quantum wells.

DETAILED DESCRIPTION OF THE INVENTION

With reference to the drawings, FIG. **1** shows a schematic energy band diagram **10** for a multiple quantum well (MQW) GaAs—GaAsN—GaAsSb active region which may be incorporated in an optoelectronic device in accordance with the invention. A GaAs barrier layer **40** is provided adjacent to a first quantum well stage **14** that includes an electron quantum well (QW) **20** of tensile strained GaAsN and a hole QW **30** of compressive strained GaAsSb. The electron quantum well layers **20** may also include indium to provide an InGaAsN layer **20** as indicated in FIG. **1**. The addition of indium allows adjustment of the lattice constant of the InGaAsN material to be either lattice matched to GaAs or have a tensile strain value which is lower than GaAsN. This allows independent control of layer thickness and strain, giving greater design flexibility. Previous approaches to type II GW laser structures on GaAs substrates have utilized a compressively-strained InGaAs electron quantum well layer. See P. Dowd, et al., "Long Wavelength (1.3 and 1.5 μm) Photoluminescence from InGaAs/GaPAsSb Quantum Wells Grown on GaAs," Appl. Phys. Lett., Vol. 75, No. 9, Aug. 30, 1999, pp. 1267–1269. The GaAs barrier layer **40** has a valence band shown at **42** and a conduction band shown at **44**.

Other higher bandgap materials may be used as the barrier layer, e.g., AlGaAs, GaAsP, and InGaP. The electron QW **20** has a valence band shown at **22** and a conduction band shown at **24**, and the hole QW **30** has a valence band shown at **32** and a conduction band shown at **34**. The conduction band **24** of the electron well **20** is provided by the GaAsN layer, while the valence band **32** of the hole-well **30** is provided by the GaAsSb layer. One or more additional stages of similar material layers may be provided adjacent to the first stage **14** to form a multiple QW stage laser. FIG. **1** shows a break **16** and a QW stage "N" **18**, to indicate that any number of QW stages may be provided in various exemplary embodiments. The one or more stages provided above the GaAs barrier layer **40** may collectively be referred to as an active region **11**.

As shown in FIG. **1**, the conduction and valence bands of the electron QW **20** and the hole QW **30** are arranged in an offset or "zig-zag" pattern. As illustrated in FIG. **1**, the electron and hole quantum wells have a type II interface in which the lowest electron energy level and the lowest hole energy level occur in adjacent layers. By contrast, in a type I quantum well the lowest electron and hole energy levels are in the same layer. During operation, in the active region **11** electrons travel between the conduction band **24** of the electron QW **20** and the valence band **32** of the hole QW **30**, recombining with holes and generating photons in the process. The transition is generally indicated by arrows **50**. The zig-zag pattern is a result of the large disparity of the band lineup of the GaAsN and GaAsSb compositions (i.e., the compositions used to form the electron QW **20** and the hole QW **30**) with that of the GaAs barrier layer **40**. GaAsN has a weak type-II band lineup with a negative valence band offset (ΔE_v) of approximately 20 meV/% N, which is shown in FIG. **1** at **26**. The GaAs—GaAsN interface also exhibits a large conduction band offset (ΔE_c), shown at **28**. The band edge of the hole QW **30** may be determined using the model solid theory. As shown in FIG. **1**, there is a relatively small ΔE_c between the GaAs conduction band **44** and the hole QW conduction band **34** and a relatively large ΔE_v between the GaAs valence band **42** and the hole QW valence band **32**.

One advantageous feature of using GaAsN and GaAsSb to form the active region **11** is that tensile-strained GaAsN and compressively-strained GaAsSb may exhibit self-strain-compensation. Such self-strain-compensation allows for the growth of any number of multiple QW structures, which in turn allows optimization of the optical gain in the resulting laser device.

Another advantageous feature associated with the GaAsN—GaAsSb active region **11** is strong carrier confinement, both for the electrons and holes in their respective QWs. For example, the electrons are confined in the electron QW **20** as a result of the relatively large ΔE_c between GaAsN and both GaAs and GaAsSb (or, where the GaAsN is surrounded between two adjacent GaAsSb regions, the relatively large ΔE_c between GaAsN and GaAsSb). In effect, the electrons in the electron QW **20** are "sandwiched" between the GaAs conduction band **44** and the GaAsSb conduction band **34**. Similarly, the holes in the hole QWs are confined by the relatively large ΔE_v between GaAsSb and GaAsN. Strong carrier confinement in the GaAsN—GaAsSb active region may allow for low device temperature sensitivity and high-output-power laser operation.

Yet another advantageous feature of using alternating layers of tensile-strained GaAsN and compressive-strained GaAsSb relates to overlap of electron wavefunctions. Conventionally, the electron wavefunctions are spread out strongly due to large differences in the electron effective masses of the GaAsSb and GaAsN layers. The use of

tensile-strained GaAsN and compressive-strained GaAsSb results in the spreading of the hole wavefunction in the hole QW valence band **32**. This may allow higher optical gain in the laser due to large electron-hole wavefunction overlap.

The use of GaAsN/GaAsSb quantum well active regions can allow emission of light having relatively long wavelengths. FIG. **2** shows the calculated relationship between emission wavelength (λ) and nitrogen and antimony content for a GaAsN—GaAsSb active region wherein the GaAsN and GaAsSb quantum well layers each had thicknesses of approximately 40 angstroms (Å). The ordinate or y-axis **102** corresponds to the emission wavelength measured in micrometers (μm). The emission wavelength was calculated based on calculated transitional energy levels including strain effects and the maximum quantum confinement effect (to illustrate the worst case scenario). The abscissa or x-axis **104** corresponds to antimony (Sb) content x in a GaAsSb layer having the formula $GaAs_{1-x}Sb_x$. The curves labeled **110**, **120**, **130**, and **140** represent the relationship between emission wavelength and antimony content (in the $GaAs_{1-x}Sb_x$ layer) for active regions having GaAsN layers with formulae $GaAs_{0.975}N_{0.025}$, $GaAS_{0.965}N_{0.035}$, $GaAs_{0.955}N_{0.045}$, and $GaAs_{0.95}N_{0.05}$, respectively.

As shown in FIG. **2**, the emission wavelength generally increases with increasing antimony content in the GaAsSb layer, as indicated by the positive slopes of the curves **110**, **120**, **130**, and **140**. The emission wavelength also increases with increasing nitrogen content, as shown by the relationship between the curves **110**, **120**, **130**, and **140**. Higher nitrogen and antimony contents in the GaAsN or GaAsSb layers results in a smaller transition energy. Higher nitrogen content in the GaAsN layers lowers the electron confined energy level, while larger antimony content in the GaAsSb layer results in a higher confined hole energy level.

In this manner, emission wavelengths of active regions having a particular configuration may be generally predicted. As shown in FIG. **2**, the design utilizing $GaAs_{0.965}N_{0.035}$ and $GaAs_{0.969}Sb_{0.031}$ results in an emission wavelength of approximately 2 μm. The extension of the emission wavelength into the 3–4 μm wavelength region is facilitated by the strain-compensating effect of the GaAsN—GaAsSb structure. For example, structures utilizing $GaAs_{0.955}N_{0.045}$ and $GaAs_{0.969}Sb_{0.031}$ layers result in emission wavelengths up to approximately 3 μm. It is believed that electron and hole confinement in the QWs improves with increasing emission wavelength due to the increased ΔE_c and ΔE_v for structures having higher nitrogen and antimony content.

According to an exemplary embodiment, a GaAsN—GaAsSb active region is configured to produce emission wavelengths of approximately 1.55 μm (e.g., with GaAsN and GaAsSb layer thicknesses of between approximately 25 and 35 Å). The active region includes GaAsN electron QWs having molar ratios of between approximately 1:0.0985:0.015 and 1:0.975:0.025 (i.e., between approximately $GaAs_{0.985}N_{0.015}$ and $GaAs_{0.975}N_{0.025}$, that is the molar nitrogen content is between approximately 1.5 and 2.5 percent). The active region also includes GaAsSb hole QWs having a molar ratio between approximately 1:0.7:0.3 and 1:0.6:0.4. The antimony content of the GaAsSb layer results in a compressive strain of between approximately 2.3 and 3.0 percent. Such a configuration may reduce or eliminate the occurrence of strain relaxation in the GaAsN—GaAsSb structure due to the thin dimension of the GaAsSb hole QWs and the strain compensating effect of the GaAsN electron QWs.

Compositions (e.g., nitrogen and antimony content) of the GaAsN and GaAsSb QWs to obtain an active region that generates light in the range of 1.55 μm may be determined by calculating transitional energy, taking into account strain and quantum confinement effects. A propagation matrix approach for multilayer heterostructures may be used to determine the quantum-confined energy levels, which allows calculation of normalized wavefunctions for the electrons and holes present in the active region.

FIG. **3** shows an energy band diagram for a single-stage active region **200** that may be used to determine appropriate nitrogen and antimony contents for the electron and hole QWs. This energy band diagram illustrates the zig-zag pattern as described above with respect to FIG. **1**. A GaAs barrier **240** has a valence band **242** and a conduction band **244**. A tensile-strained GaAsN electron QW **220** has a valence band **222** and a conduction band **224**, and a compressive-strained GaAsSb hole QW **230** has a valence band **232** and a conduction band **234**. A single-stage active region may be used to approximate the emission wavelength of systems having a greater number of stages, since coupling of wave functions in multiple-stage active regions does not greatly modify the emission wavelength obtained by such multiple-stage active regions.

FIG. **4** illustrates the relationship between wavefunction overlap and emission wavelength for a single-stage QW active region (as in FIG. **3**) having a GaAsSb hole QW composition of $GaAs_{0.65}Sb_{0.35}$. FIG. **4** also shows the relationship between nitrogen content in the GaAsN layer and emission wavelength. For this exemplary embodiment, the electron and hole QW layers each have a thickness of approximately 30 Å. It is understood that this is an example for illustrative purposes and other thicknesses may be used for the QW layers. The abscissa **302** represents emission wavelength in μm. A first ordinate **304** represents the degree of electron and hole wavefunctions overlap Γ_{e-hh} (e.g., 0.6=60 percent overlap). A second ordinate **306** represents the nitrogen content of the GaAsN layer in molar percent (e.g., 2.5=$GaAs_{0.975}N_{0.025}$).

A first curve **310** in FIG. **4** represents the relationship between Γ_{e-hh} and emission wavelength, and a second curve **320** represents the relationship between nitrogen content in the GaAsN layer and emission wavelength. As shown in FIG. **4**, the degree of wavefunction overlap generally decreases with increasing emission wavelength, while emission wavelength generally increases with increased nitrogen content in the GaAsN layer.

While the wavefunction overlap tends to decrease as the emission wavelength is extended in a single-stage QW system, a wavefunction overlap of approximately 60 percent may be achieved at an emission wavelength of approximately 1.5 μm. According to an alternative embodiment in which a QW active region having a wavelength of 1.3 μm is provided, a wavefunction overlap of approximately 70 percent may be achieved. Wavefunction overlaps greater than approximately 45 percent are also predicted for emission wavelengths above 2 μm. Optimization of the nitrogen and antimony content for the GaAsN and GaAsSb layers is described below for a QW system having an emission wavelength of approximately 1.55 μm according to a preferred embodiment. It should be understood that for alternative embodiments having differing emission wavelengths (e.g., 1.3 μm or other wavelengths greater or less than 1.55 μm), similar optimization schemes may be employed.

FIG. **5** illustrates by the graph **420** the relationship between nitrogen and antimony content for GaAsN and GaAsSb layers of a single-stage QW system to achieve an emission wavelength of approximately 1.55 μm. The GaAsN

and GaAsSb layers have a thickness of approximately 30 Å. FIG. **5** also shows by the graph **410** the relationship between wavefunction overlap and antimony composition in the GaAsSb layer. The abscissa **402** represents the antimony content of the GaAsSb layer in molar percent (e.g., 30=$GaAs_{0.7}Sb_{0.3}$). A first ordinate **304** represents the degree of electron and hole wavefunctions overlap $\Gamma_{e\text{-}hh}$ (e.g., 0.6=60 percent overlap). A second ordinate **306** represents the nitrogen content of the GaAsN layer in molar percent (e.g., 2.5=$GaAs_{0.975}N_{0.025}$).

As shown in FIG. **5**, various compositions of the 30 Å thick GaAsSb and 30 Å thick GaAsN QWs can be chosen to achieve an emission wavelength of approximately 1.55 μm. Nitrogen content in the GaAsN layer must generally be increased to compensate for a decreased antimony content in the GaAsSb layer to achieve an emission wavelength of approximately 1.55 μm. A GaAsSb composition having a large antimony content allows the use of a GaAsN composition having a reduced nitrogen content. One advantageous feature of providing a GaAsN QW having a reduced nitrogen content is that higher optical luminescence of the GaAsN QW may be achieved. The nitrogen content in the GaAsN layer, however, is preferably large enough to provide relatively strong electron confinement in the GaAsN electron QWs.

FIG. **6** illustrates the wavefunctions overlap for electron (Ψ_{el}) and heavy-hole (Ψ_{hh}) wavefunctions in a single-stage active region having an approximately 30 Å thick layer of $GaAs_{0.98}N_{0.02}$ and an approximately 30 Å thick layer of $GaAs_{0.65}Sb_{0.35}$. A first curve **510** represents the electron wavefunction, and a second curve **520** represents the heavy-hole wavefunction. The heavy-hole wavefunction is used because transitions of electrons to heavy hole levels are favored due to the compressive strain of the GaAsSb hole QW. As shown in FIG. **6**, a wavefunctions overlap of approximately 59.4 percent is obtained for a single-stage active region having the composition described above.

Wavefunction overlap in a MQW design may be increased by providing strong coupling for the electron wavefunction, which provides a large field in the GaAsSb region for the electron- and hole-wavefunctions. According to an exemplary embodiment, relatively strong coupling of the QWs may be achieved by reducing the size of the QWs. According to a preferred embodiment, relatively strong coupling is achieved by implementing a MQW system design. Such multiple-QW system design includes QWs having thicknesses that are preferably above approximately 30 Å to provide strong carrier confinement and good control in the MOCVD growth processes. FIG. **7** illustrates an MQW design (i.e., 5 stage) that has a wavefunction overlap of approximately 74.3 percent between an electron wavefunction curve **560** and a heavy-hole wavefunction curve **570**.

FIG. **8** illustrates the relationship between wavefunction overlap and the number of stages included in a MQW system having approximately 30 Å thick layers of $GaAs_{0.98}N_{0.02}$ and $GaAs_{0.65}Sb_{0.35}$. The abscissa **602** represents the number of stages in the multiple-QW system, a first ordinate **604** represents the electron and heavy-hole wavefunction overlap, and a second ordinate **606** represents the emission wavelength in μm. As shown by the graph **610** in FIG. **8**, wavefunction overlap generally increases with an increasing number of stages, with a three-stage QW system having an overlap above approximately 72 percent. FIG. **8** also shows the relationship between emission wavelength and the number of stages provided in a multiple-QW system. As indicated by the graph **620**, increasing the number of stages generally increases the emission wavelength. As previously discussed, however, the overall impact of increasing the number of QWs in the system on the emission wavelength is relatively small. For example, as shown in FIG. **8**, a single-stage QW system having the composition described above has an emission wavelength of approximately 1.5 μm, while a five-stage QW system has an emission wavelength of approximately 1.51 μm.

Coupling of the electron and heavy-hole wavefunctions may be achieved by reducing the thickness of the individual layers of GaAsN and/or GaAsSb. FIG. **9** illustrates a graph **710** representing the relationship between wavefunction overlap and thickness of the QW layers in a 5-stage QW system having an emission wavelength of 1.5 μm. The abscissa **702** represents the thickness of the QW layers in angstroms, the first ordinate **704** represents the electron and heavy-hole wavefunction overlap, and the second ordinate **706** represents the nitrogen content in the GaAsN QW.

The coupling of the wavefunctions may be optimized as appropriate. The graph **710** generally shows increasing wavefunction overlap with decreasing thickness of QW layers, where the thicknesses of the GaAsN and GaAsSb layers are substantially equal. For example, the graph **710** shows a wavefunction overlap of approximately 89 percent for QW layer thicknesses of 20 Å. The GaAsN and GaAsSb layers may also have different thicknesses.

The graph **720** illustrates a generally increasing N content with decreasing thickness of the GaAsN layer for a 30 Å $GaAs_{1-x}N_x$/30 Angstrom $GaAs_{0.65}Sb_{0.35}$ layer.

The Type II quantum well active region as 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, examples of edge emitting and surface emitting laser structures are discussed below.

FIG. **10** is a schematic cross-sectional view of an example of the present invention embodied in a vertical cavity surface emitting laser (VCSEL) **800**. The VCSEL **800** includes a substrate **810** of n-doped GaAs, a lower confinement layer **820** (of, e.g., GaAs or AlGaAs), an active region layer **830** having a multiple quantum well structure and a GaAs barrier layer as described above, an upper confinement layer **840** (of GaAs or AlGaAs) and a capping layer **850** of, e.g., p+-doped GaAs. An upper distributed Bragg reflector (DBR) **845**, formed, e.g., of multiple (e.g., 22) alternating layers of AlGaAs/GaAs, and a lower DBR **825** 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 **860** and **870** 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 **800** to generate lasing in the active region. An aperture or opening **872** is formed in the electrode layer **800** through which a light beam may be emitted. A layer of $AlAs/Al_2O_3$ **875** with an opening **876** therein interposed between the upper confinement layer **840** and the upper DBR **845** to confine current flow through the opening **876** and provide light generation in the active region under the opening. The top surface **812** of the substrate **810** may be oriented in a (100) crystallographic direction, and the various layers formed above the substrate **810** can be epitaxially grown thereon in a conventional fashion. According to alternative embodiments, other crystallographic directions for the top surface **812** and subsequent layers may be used.

The epitaxially-grown layers may be provided above the substrate **810** using metal organic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE).

An exemplary active region **830** includes a multiple QW structure having, e.g., 5 QW stages, for a total of 10 layers. As described above, the GaAsN layers form electron QWs, while the GaAsSb layers form hole QWs. Of course, a different number of stages or layers may be used in the active region. For example, six layers may be used to form an active region having three QW stages. According to an exemplary embodiment, the thickness of each of the individual layers in the active region **830** is approximately 30 Å, resulting in a thickness for the active region of approximately 300 Å where a five-stage QW structure is provided. If desired, the thickness of the various active region layers may differ from one another. For example, the GaAsN layers may have a thickness that is greater or less than the thickness of the GaAsSb layers. Both layers in one or more of the stages may have a thickness that is greater or less than the thickness of other stages. The thicknesses and compositions of the layers in the active region may be chosen in accordance with the considerations discussed above.

The invention may also be embodied in edge emitting lasers. For purposes of illustration, FIG. **11** shows a schematic diagram of a distributed feedback edge-emitting laser **900** fabricated in accordance with another exemplary embodiment. The laser **900** includes a substrate **910** of n-doped GaAs, a lower cladding layer **920** (e.g., n-doped AlGaAs or n-doped InGaP), a lower optical confinement layer **930** (e.g., GaAs), an active region **940** having a multiple quantum well structure as discussed above, an upper confinement layer **950** (e.g., GaAs), a distributed feedback grating **960** (DFB) formed in the upper confinement layer, an upper cladding layer **970** (e.g., P-AlGaAs or p-InGaP), a capping layer **980** (e.g., p-doped GaAs), an insulating layer **990** (e.g., silicon dioxide), and electrode layers **1000** and **1010** preferably formed of a metal to provide electrical contacts through which voltage may be applied to generate light in the active region **940**. Although a distributed feedback grating **960** is illustrated for purposes of providing grated 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 **995** in the insulating layer **990** through which current can flow from the electrode **1000**. However, other types of gain guiding and/or lateral confinement may be utilized. The top surface **912** of the substrate **910** may be oriented in a (100) crystallographic direction, and the various layers formed above the substrate **910** may be epitaxially grown thereon. According to alternative embodiments, other crystallographic directions for the top surface **912** and subsequent layers may be used. The epitaxially-grown layers may be provided above the substrate **910** using metal organic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE).

The active region **940** includes a multiple QW structure having, e.g., 3 QW stages, for a total of 6 layers. As described above, GaAsN layers form electron QWs, while GaAsSb layers form hole QWs. 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 **940** 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 **1000** in FIG. **12**. The laser **1000** includes a substrate **1001** of GaAs, generally n-doped, an n-doped cladding layer **1002** (e.g., AlGaAs or InGaP), a strained multiple quantum well-single confinement heterostructure (MQW-SCH) active region layer **1004** in accordance with the invention, an upper p-type cladding layer **1006** (e.g., AlGaAs or InGaP), an n-GaAs blocking layer **1008** with a central opening **1009** therein (e.g., P—AlGaAs), and a cap layer **1011** (e.g., P—GaAs). A layer of metal **1012** on the bottom surface of the substrate **1001** provides the lower electrode, and a layer of metal **1014** on the top surface of the cap layer **1011** provides the upper electrode. When voltage is applied between the upper electrode **1014** and the lower electrode **1012**, current flows in the opening **1009** in the blocking layer **1008**, with current being blocked elsewhere by the n-p junction provided by the blocking layer **1008** and the p-type cladding layer **1006**. Optical feedback to provide lasing action in the active region is provided by a high reflection coating mirror **1015** at one of the edge facets and a lower reflection coating **1016** at the other edge facet which provides partial reflection and allows a beam of light **1018** to exit from the edge facet of the laser.

The active region in the present invention may also be embodied in a decoupled quantum well structure, as illustrated in FIG. **13**. The electron quantum well layers **20** and hole quantum well layers **30** are formed as discussed above with respect to FIG. **2**. However, an additional high-bandgap layer **1020** of a material such as GaAs may be utilized between the GaAsN/GaAsSb sections to separate them, as illustrated in FIG. **13**. This separation preserves the two-dimensional behavior of the individual quantum well sections. If the GaAsN/GaAsSb quantum well sections are strongly coupled, they behave more like a bulk active layer and thereby lose certain of the benefits of a two-dimensional structure. The tradeoff incurred in using the additional high bandgap layer **1020** is a lower wavefunction overlap between electron and hole because the quantum well sections are decoupled.

The composition of the GaAsN/GaAsSb materials of the quantum wells may be chirped or graded in the transverse direction across the set of quantum wells to change the energy levels of the conduction band and valence band of each of the quantum wells, as illustrated in FIG. **14**. Chirping or grading the composition of the quantum wells in this fashion provides the potential for a broad gain spectrum.

The thickness of the GaAsN/GaAsSb layers in the quantum wells may also be chirped or graded in the transverse direction from quantum well to quantum well, is illustrated in FIG. **15**. Chirping or grading the thickness of the quantum well layers in this fashion also provides the potential for a broad gain spectrum. A large spectral gain bandwidth obtained by grading the thickness or material of the quantum wells is a useful feature for amplifiers or gain sections in external cavity tunable lasers.

As previously indicated, the present invention having the active region as discussed above may be embodied in various types of optoelectronic devices and is not limited to diode lasers. Examples of such other devices include light emitting diodes, amplifiers, and gain sections for external cavities. Such devices may have structures similar to those discussed above for exemplification with respect to diode lasers but without structures for providing optical feedback for lasing action.

Implementation of GaAsN—GaAsSb active regions into vertical cavity surface emitting lasers (VCSELs), grating coupled surface emitting lasers, and edge-emitting lasers allows for production of monolithic, lower cost, longer wavelength (e.g., 1.3 to 1.55 μm or longer, etc.) sources, as compared with conventional lasers. Strong carrier confinement (for low device temperature sensitivity), large overlap of electron-hole wavefunctions (for high gain), and ability to implement strain compensation (for multiple QW active designs) also may be achieved through the use of GaAsN—GaAsSb active regions in accordance with the invention.

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. An optoelectronic device comprising:

a multilayer semiconductor structure including a GaAs substrate and an active region, the active region comprising at least a hole quantum well layer of GaAsSb and electron quantum well layers adjacent to the hole quantum well layer at least one of which comprises GaAsN to provide a type II quantum well structure, wherein the electron quantum well layers and hole quantum well layer form a first quantum well stage, and wherein the active region comprises a plurality of quantum well stages adjacent to each other having the same structure as the first quantum well stage, and including a transitional layer of GaAs between each quantum well stage.

2. The device of claim **1** wherein the electron quantum well layers are in tensile strain and the hole quantum well layer is in compressive strain.

3. The device of claim **1** wherein the thickness of each electron quantum well layer and the hole quantum well layer is between approximately 20 and 50 angstroms.

4. The device of claim **1** including a barrier layer adjacent to the GaAsN electron quantum well layer.

5. The device of claim **4** wherein the barrier layer material comprises GaAs.

6. The device of claim **1** wherein the antimony content of the hole quantum well layer is approximately 35 molar percent.

7. The device of claim **1** wherein the multilayer semiconductor structure forms a vertical cavity surface emitting laser.

8. The device of claim **1** wherein the multilayer semiconductor structure forms an edge-emitting laser.

9. The device of claim **1** wherein the active region generates light having a wavelength greater than approximately 1.3 μm.

10. The device of claim **1** wherein the active region generates light having a wavelength of approximately 1.55 μm.

11. The device of claim **1** wherein at least one of the electron quantum well layers includes indium therein to provide an InGaAsN electron quantum well layer.

12. An optoelectronic device comprising:

a multilayer semiconductor structure including a GaAs substrate and an active region, the active region comprising at least a hole quantum well layer of GaAsSb and electron quantum well layers of GaAsN adjacent to the hole quantum well layer to provide a type II quantum well structure, wherein the electron quantum well layers are in tensile strain and the hole quantum well layer is in compressive strain, wherein the electron quantum well layers and hole Quantum well layer form a first quantum well stage, and wherein the active region comprises a plurality of quantum well stages adjacent to each other having the same structure as the first quantum well stage, and including a transitional layer of GaAs between each Quantum well stage.

13. The device of claim **12** wherein the thickness of each of the electron quantum well layer and the hole quantum well layer is between approximately 20 and 50 angstroms.

14. The device of claim **12** including a barrier layer adjacent to a GaAsN electron quantum well layer.

15. The device of claim **12** wherein the antimony content of the hole quantum well layer is approximately 35 molar percent.

16. An optoelectronic device comprising:

a multilayer semiconductor structure including a GaAs substrate and an active region, the active region comprising at least a hole quantum well layer of GaAsSb and electron quantum well layers adjacent to the hole quantum well layer at least one of which comprises InGaAsN to provide a type II quantum well structure.

17. The device of claim **16** wherein the electron quantum well layers are in tensile strain and the hole quantum well layer is in compressive strain.

18. The device of claim **16** wherein the lnGaAsN layer is lattice matched to GaAs.

19. The device of claim **16** wherein the thickness of each of the electron quantum well layers and the hole quantum well layer is between approximately 20 and 50 angstroms.

20. The device of claim **16** including a barrier layer adjacent to the GaAsN electron quantum well layer.

21. The device of claim **16** wherein the electron quantum well layers and hole quantum well layer form a first quantum well stage, and wherein the active region comprises a plurality of quantum well stages adjacent to each other having the same structure as the first quantum well stage.

22. The device of claim **21** including a transitional layer of GaAs between each quantum well stage.

23. A semiconductor laser comprising:

(a) a multilayer semiconductor structure including a GaAs substrate and an active region, the active region comprising at least a hole quantum well layer of GaAsSb and electron quantum well layers adjacent to the hole quantum well layer at least one of which comprises lnGaAsN to provide a type II quantum well structure; and

(b) means for providing optical feedback to provide lasing action in the active region.

24. The laser of claim **23** wherein the electron quantum wells layer are in tensile strain and the hole quantum well layer is in compressive strain.

25. The laser of claim **23** wherein the thickness of each of the electron quantum well layer and the hole quantum well layer is between approximately 20 and 50 angstroms.

26. The laser of claim **23** including a barrier layer adjacent to the GaAsN electron quantum well layer.

27. The laser of claim **23** wherein the electron quantum well layer and hole quantum well layer form a first quantum well stage, and wherein the active region comprises a plurality of quantum well stages adjacent to each other having the same structure as the first quantum well stage.

28. The laser of claim **27** including a transitional layer of GaAs between each quantum well stage.

29. The laser of claim **23** wherein the antimony content of the hole quantum well layer is approximately 35 molar percent.

30. The laser of claim **23** wherein the multilayer semiconductor structure forms a vertical cavity surface emitting laser.

31. The laser claim **23** wherein the multilayer semiconductor structure forms an edge-emitting laser.

32. The laser of claim **23** wherein the active region generates light having a wavelength greater than approximately 1.3 μm.

33. The laser of claim **23** wherein the active region generates light having a wavelength of approximately 1.55 μm.

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