

ARTICLE COMPRISING A QUANTUM WELL LASER**Field of the Invention**

This invention pertains to quantum well lasers, and articles that comprise such lasers.

5 Background of the Invention

GaAs-based as well as InP-based quantum well lasers are known. Such lasers typically comprise an active region that contains one or more quantum wells, the active region sandwiched between two waveguide layers, the combination in turn sandwiched between two cladding layers. Adjacent quantum wells are separated by
10 a barrier layer.

Although quantum well lasers are widely used, prior art quantum well lasers (especially InP-based quantum well lasers) have shortcomings. For instance, in order to overcome problems (e.g., a small conduction band discontinuity between InP and the active region material, as well as a low potential barrier for electrons
15 between the active and cladding regions) inherent in the commonly used InGaAsP/InP material system, it has been found necessary to use relatively highly doped cladding layers. This results in relatively high absorption of the lasing mode , necessitating use of a multi quantum well (MQW) active region. Furthermore, due to the noted and other characteristic of InGaAsP/InP quantum well lasers, such lasers
20 typically exhibit undesirably strong temperature dependence of threshold current and external quantum efficiency. The referred-to strong temperature dependences are particularly detrimental for uncooled lasers which typically have to be operable over a rather large temperature range, e.g., -40 to +85°C for some uncooled optical communication lasers.

25 C. E. Zah et al., OFC 94 Technical Digest, Vol. 4, p. 204 disclosed an InP-based strained MQW laser with improved temperature performance. The improvement resulted from the substitution of AlInGaAs for the conventionally used InGaAsP, with attendant increased electron confinement energy. The characteristic temperature (T_0) of the threshold current of the laser was reported to be 80K.

30 S. Hausser et al., Applied Physics Letters, Vol. 62(7), p. 663 disclosed a InGaAsP/InP MQW laser that comprised an InP hole barrier layer between the MQW region and the n-side cladding layer. The barrier served to prevent hole leakage into the n-side cladding region, and was said to result in improved temperature performance of the laser. T_0 was reported to be 62K. The authors
35 report also fabrication of a laser "...that has an InP electron barrier but no hole barrier adjacent to the quantum wells...", and concluded that the (InP) hole barrier is very

important but that the (InP) electron barrier "...has only a minor effect and is not really necessary..."

In view of the potential importance of reduced temperature dependence of laser characteristics, especially for uncooled lasers, it would be highly desirable to
5 have available a laser that can have relatively low temperature dependence of, e.g., threshold current and external quantum efficiency. This application discloses such a laser.

Summary of the Invention

The invention is defined by the claims. In a broad aspect the invention
10 is embodied in an article that comprises a quantum well semiconductor laser having features that can result in improved laser characteristics.

More specifically, the laser comprises a multilayer semiconductor structure on a substrate, and contacts that facilitate flowing a current through the multilayer structure. The multilayer structure comprises a (optionally n-doped) n-
15 side waveguide layer, an active region comprising at least one quantum well, and a (optionally p-doped) p-side waveguide layer, with the active region disposed between said two waveguide layers.

The n-side waveguide layer is disposed between the active region and an n-doped cladding layer, and the p-side waveguide layer is disposed between the
20 active region and a p-doped cladding layer. In preferred embodiments the multilayer structure further comprises a hole stopper layer disposed between the at least one quantum well and the n-side waveguide layer, the hole stopper layer selected to provide a barrier for the flow of holes from the active region to the n-side waveguide layer.

25 Significantly, the multilayer structure further comprises an electron stopper layer disposed between the at least one quantum well and the p-side waveguide layer, the electron stopper layer selected to provide a barrier for the flow of electrons from the active region to the p-side waveguide layer. The electron stopper layer material is selected to have bandgap energy E_g at least as large as the
30 bandgap energy of InP, with more than 50% of the offset associated with the discontinuity of the conduction band. The bandgap energy of InP is about 1.35 eV. If a hole stopper layer is provided then the electron stopper layer will have a chemical composition that differs from the chemical composition of the hole stopper layer. Material of the hole stopper layer typically has an electron affinity that is
35 greater than that of the material of the electron stopper layer. In a preferred embodiment the laser is InP-based, with the active region comprising AlInGaAs, and

the laser having a characteristic temperature (T_0) of the threshold current greater than 80K.

The terminology "selected to provide a barrier to the flow of electrons/holes" does not imply complete stoppage of the flow of electrons/holes.

5 Instead, the terminology is to be understood to mean that the presence of the given stopper layer results in at least substantially lower flow, at a device operating temperature, of the relevant charge carrier from the active region to the relevant waveguide layer, as compared to the flow observed in an otherwise identical comparison device that does not comprise the given stopper layer.

10 Each of the hole stopper layer and electron stopper layer provides a potential barrier to the flow of holes and electrons, respectively, from the active region to the n-side and p-side waveguide and cladding regions, respectively, with the "height" of the potential barrier typically being at least about 50 meV (corresponding approximately to $2kT$ at $T = 300$ K, where k is Boltzmann's
15 constant). Clearly, a stopper layer has to have sufficient thickness (exemplarily >10 nm) such that the carrier tunneling probability through the stopper layer is insignificant (e.g., $<1\%$).

The layer structure of a laser according to the invention can be formed on either a p-doped or an n-doped substrate, the substrate can be any appropriate
20 semiconductor material (typically InP or GaAs), and the layer structure can be formed by any appropriate technique, e.g., MOCVD, MBE, CVD, CBE, or MOMBE. Furthermore, lasers according to the invention comprise lateral confinement means, e.g., a mesa structure or a buried heterostructure. Such means are well known in the art and do not require further exposition. All lateral current
25 and/or optical mode confinement means are contemplated.

Brief Description of the Drawings

FIGs. 1 and 2 show schematic band edge diagrams of prior art lasers;

FIGs. 3 and 4 show schematic band edge diagrams of lasers according to the intention;

30 FIG. 5 shows the refractive index of AlInGaAs, lattice matched to InP, as a function of the energy gap;

FIG. 6 shows an energy diagram of an exemplary quantum well;

FIG. 7 presents curves of light power vs. injection current for an exemplary laser according to the invention; and

FIG. 8 shows a curve of internal quantum efficiency vs. injection current.

Detailed Description of Some Preferred Embodiments

FIG. 1 schematically depicts the band edge diagram of a (normally biased) prior art laser, namely, the laser with InP hole barrier disclosed by S. Hausser et al. (op. cit.), and was computed, using the known "PADRE" program (see R. F. Kazarinov et al., IEEE Journal of Quantum Electronics, Vol. 30, p. 49 (1994), and relevant references therein), from data provided in the paper. Reference numerals 10 and 11 refer, respectively, to the conduction band edge and valence band edge, respectively, numerals 12 and 13 refer to the electron Fermi level and the hole Fermi level, respectively, and numerals 14-19 refer to the p-cladding layer, p-side waveguide layer, active region, hole stopper layer, n-side waveguide layer, and n-cladding layer, respectively.

FIG. 2 schematically depicts the computed band edge diagram of another (normally biased) prior art laser, namely, of the laser with InP "electron barrier" described on p. 664 of the above referred to paper by S. Hausser et al. The laser of FIG. 2 is identical to the laser of FIG. 1, except that in the former the InP "barrier" layer is placed to the p-contact side of the quantum well structure. Numerals 26 and 27 refer, respectively, to the active region and the "electron barrier" layer. According to the Hausser et al. paper, the laser of FIG. 2 exhibits hole leakage, and the presence of the InP electron barrier has only a minor effect on electron leakage.

As can be seen from FIG. 2, InP layer 27 provides a relatively insignificant barrier for the (unwanted) flow of electrons from the active region to layer 15, and actually provides a somewhat higher barrier for the (required) flow of holes from layer 15 to the active region, thereby impeding the injection of holes into the active region.

A preferred laser according to the invention has both a hole stopper layer and an electron stopper layer, with the material of the former differing in chemical composition from the material of the latter. Specifically, the materials are selected such that the material of the hole stopper layer has greater electron affinity than the material of the electron stopper layer, and therefore the stopper layers substantially do not impede injection of carriers into the active region. Exemplarily, the laser is a GaAs-based laser, the hole stopper layer is GaAlAs, and the electron stopper layer is GaInP. The remainder of the laser structure can be conventional.

Next we will describe an exemplary particularly preferred embodiment of the invention. Relevant parameters of the layer structure of the laser are recited in Tables I and II. The compositions are selected to be lattice matched to InP. The p-dopant exemplarily is Zn but can be C or any other p-dopant, and the n-dopant exemplarily is Si but can be any other n-dopant.

Table I

	LAYER	COMPOSITION	THICKNESS (nm)	DOPING LEVEL (cm ⁻³)
10	cladding layer	p-AlInAs		5x10 ¹⁷
	waveguide	p-AlInGaAs (I)	120	2x10 ¹⁷
	electron stopper	p-AlInAs	10	2x10 ¹⁷
	barrier	p-AlInGaAs (II)	10	1x10 ¹⁷
	active	AlInGaAs	4	undoped
15	barrier	p-AlInGaAs (II)	10	1x10 ¹⁷
	active	AlInGaAs	4	undoped
	barrier	n-AlInGaAs (II)	10	1x10 ¹⁷
	active	AlInGaAs	4	undoped
	barrier	n-AlInGaAs (II)	10	1x10 ¹⁷
20	hole stopper	n-InP	8	1x10 ¹⁷
	waveguide	n-AlInGaAs (I)	120	3x10 ¹⁷
	cladding layer	n-AlInAs		1x10 ¹⁸
	substrate	n-InP		2x10 ¹⁸

Table II

MATERIAL	E_g (eV)	n
AlInAs	1.47	3.16
AlInGaAs	0.770	3.55
AlInGaAs (I)	1.02	3.455
AlInGaAs (II)	1.190	3.322
InP	1.35	3.21

5 As is conventional, expressions such as AlInGaAs are not chemical formulas but merely recitations of the constituent elements. Thus, as an example, the expression "AlInGaAs" is to be understood to stand for the quaternary alloy $Al_{1-x-y}In_xGa_yAs$.

10 Table II shows the energy gaps (E_g) and refractive indices (n) of the materials of Table I. As those skilled in the art know, a given value of E_g for a particular ternary or quaternary composition can be directly translated into an equivalent wavelength and into a specific composition. For instance, $E_g = 1.47$ eV corresponds to a value $x = 0.48$ for $Al_xIn_{1-x}As$. FIG. 5 shows the refractive index of AlInGaAs as a function of energy gap, for material that is lattice matched to InP.

15 FIG. 3 shows schematically the band edge diagram of the layer structure according to Tables I and II, under normal bias conditions. Numerals 30 and 31 refer to the conduction band edge and valence band edge, respectively, and numerals 32 and 33 refer to the electron and hole Fermi levels, respectively. Numerals 34-40 refer to p-side cladding layer, p-side waveguide layer, electron stopper layer, active region, hole stopper layer, n-side waveguide layer and n-side cladding layer, respectively.

20 The band structure shown in FIG. 3 also was computed using the "PADRE" program. The difference between the electron and hole Fermi levels is smaller in the waveguide layers than in the active region. Thus, the total recombination rate in the waveguide layers is reduced due to the presence of the stopper layers. Those skilled in the art will appreciate that the potential spikes at the interfaces between cladding and waveguide layers (especially on the n-side) can readily be reduced by replacing the abrupt interfaces of the structure of Table I by compositionally graded interfaces, and we contemplate lasers with one or more graded interfaces as well as lasers with abrupt interfaces.

InP and AlInAs that is lattice matched to InP have almost equal values of E_g , but the electron affinity of the former is about 0.35 eV larger than that of the latter, making AlInAs useful as electron stopper layer material in InP-based lasers. The presence of the stopper layer does not impede the injection of carriers into the active region, but can drastically reduce the thermionic emission of carriers out of the active region.

FIG. 4 shows the band diagram of a (normally biased) laser that comprises InP cladding layers and an electron stopper layer but does not comprise a hole stopper layer. Provision of only an appropriate electron stopper layer can result in significant advantages. However, preferred embodiments of the invention generally also comprise a hole stopper layer.

In FIG. 4 numerals 41-44 refer, respectively, to the conduction band edge, valence band edge, electron Fermi level and hole Fermi level, numerals 45-47 refer to the p-doped cladding layer, electron stopper layer and p-side waveguide layer, and numerals 48-50 refer to the active region, n-side waveguide layer and n-doped cladding layer. Exemplarily, layers 45, 46, 47, 49 and 50 are, respectively, InP, AlInGaAs, AlInAs, AlInGaAs and InP. The active region 48 comprises AlInGaAs of two compositions.

The presence of the stopper layers (or layer) in lasers according to the invention can provide increased design freedom, exemplarily substantially decoupling the design of the electrical aspects of the laser from the design of the optical aspects. This exemplarily makes it possible to select the material of the waveguide layers to have a relatively low value of E_g (exemplarily $E_g = 1.02$ eV for a laser designed to lase at $1.3 \mu\text{m}$), and therefore having a relatively large value of refractive index. This in turn can result in significant improvement in the optical occupation factor of the active region.

FIG. 6 shows the energy diagram of a 4 nm wide AlInGaAs ($E_g = 0.77$ eV) quantum well between AlInGaAs ($E_g = 1.19$ eV) barriers. In this combination, electrons have only one bound state (61), with energy 0.138 eV. Holes have two bound states (62, 63), with energies 0.024 and 0.086 eV. The energy difference between the two hole states exceeds $2 kT$ at $T = 300$ K. FIG. 6 also shows the values of E_g of the quantum well and of the barriers, the conduction band offset ΔE_c and the valence band offset ΔE_v , and the energy difference E_o between the electron state and the lowest hole state. In FIG. 6, the energies of the electron and hole states are counted from the bottom of the corresponding bands.

The quantum well of FIG. 6 has highly quantized electron and hole states, with only the lower hole energy level substantially populated. This substantially ideally 2-dimensional electron and hole gas facilitates high gain for a given carrier concentration.

5 FIG. 7 shows computed light power vs. injection current at 27°C and 87°C for a laser according to Table I, with 500 μm cavity length and 3 μm mesa width. The corresponding threshold currents are 5 mA and 9 mA, respectively, and the threshold current densities are 330 A/cm^2 and 594 A/cm^2 . The T_0 value of the laser is 102 K, and the slope efficiencies are 80% at 27°C and 60% at 87°C. Our
10 calculations also indicate that the internal quantum efficiency makes no significant contributions to the external efficiency even at 87°C.

 FIG. 8 shows an exemplary curve of internal quantum efficiency vs. injection current for the laser of Table I, at 87°C. The curve shows that substantially all carrier re-combination above threshold takes place in the active region,
15 substantially independent of injection current.

Lasers according to the invention are advantageously used in most, if not all, situations where prior art semiconductor lasers are currently used. Exemplarily, they are used in optical fiber communication systems as sources of signal radiation at, e.g., about 1.3 μm or 1.55 μm . As is well known, such a system
20 comprises, in addition to the signal source, a signal detector and optical fiber that signal-transmissively connects the source and the detector.

**Claims:**

1. An article comprising a laser comprising a multilayer semiconductor structure (34-40; 45-50) on a substrate and contacts that facilitate flowing a current through the multilayer structure, the multilayer structure having a conduction band edge and comprising an n-side waveguide layer (39; 49), an active region (37; 48) comprising at least one quantum well, and a p-side waveguide layer (35; 46), the active region being disposed between said waveguide layers;

CHARACTERIZED IN THAT

- the multilayer structure further comprises an electron stopper layer (36; 47) disposed between said at least one quantum well and the p-side waveguide layer, the electron stopper layer selected to have a bandgap energy E_g at least as large as the bandgap energy of InP, with more than 50% of an energy offset associated with a discontinuity of the conduction band edge, and selected to provide a barrier for the flow of electrons from the active region to the p-side waveguide layer.

2. An article comprising a multilayer semiconductor structure (34-40) on a substrate and contacts that facilitate flowing a current through the multilayer structure, the multilayer structure having a conduction band edge and comprising an n-side waveguide layer (39), an active region (37) comprising at least one quantum well, and a p-side waveguide layer (35), with the active region disposed between said waveguide layers, the multilayer structure further comprising a hole stopper layer (38) disposed between said at least one quantum well and said n-side waveguide layer, and selected to provide a barrier for the flow of holes from the active region to the n-side waveguide layer;

CHARACTERIZED IN THAT

- the multilayer structure further comprises an electron stopper layer (36) disposed between said at least one quantum well and the p-side waveguide layer, the electron stopper layer selected to provide a barrier for the flow of electrons from the active region to the p-side waveguide layer and having a chemical composition different from the chemical composition of the hole stopper layer, the chemical compositions of the respective stopper layers selected such that the material of the hole stopper layer has an electron affinity that is greater than the electron affinity of the material of the electron stopper layer.

3. An article according to claim 2, wherein the material of the electron stopper layer has a bandgap energy at least as large as the bandgap energy of InP,



This Sheet Has Been Replaced



- 10 -

with more than 50% of an energy offset associated with a discontinuity of the conduction band edge.

4. An article according to any of the preceding claims, wherein the substrate is selected from the group consisting of InP and GaAs.

5 5. An article according to claim 4, wherein the active region comprises two or more quantum wells, with a barrier layer between two adjacent quantum wells, each of said two adjacent quantum wells comprising AlInGaAs of a first composition, and the barrier layer comprising AlInGaAs of a second composition.

10 6. An article according to any of the preceding claims, wherein with each of said stopper layers is associated a potential barrier, each said potential barrier being at least 50 meV.

7. An article according to any of the preceding claims, further comprising lateral confinement means adapted for lateral confinement of one or both of an electrical current and an optical mode.

15 8. An article according to any of the preceding claims, wherein the multilayer structure comprises at least one compositionally graded interface between two adjacent layers.

9. An article according to any of the preceding claims, wherein the laser has a threshold current characteristic temperature $T_0 > 80K$.

20 10. An article according to any of the preceding claims, wherein the at least one quantum well has a thickness selected to provide a single electron energy level (61) and two or more hole energy levels (62, 63) in the quantum well, the energy difference between said two hole energy levels being at least 2 kT, where k is Boltzmann's constant and T is a laser operating temperature in degrees Kelvin.

25 11. An article according to any of the preceding claims, wherein the article is an optical fiber communication system.