A laser comprises a semiconductor body having a pair of end faces and including an active region comprising adjacent active and guide layers which is spaced a distance from the end face and a passive region comprising adjacent non-absorbing guide and mode control layers which extends between the active region and the end face. The combination of the guide and mode control layers provides a weak positive index waveguide in the lateral direction thereby providing lateral mode control in the passive region between the active region and the end face.

24 Claims, 4 Drawing Figures
SEMICONDUCTOR LASER HAVING A NON-ABSORBING PASSIVE REGION WITH BEAM GUIDING

The invention described herein was made in the performance of work under NASA Contract No. NAS 1-17441 and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958 (72 Stat. 435; 42 U.S.C. 2457).

The invention relates to a semiconductor laser and, in particular, to a laser having a non-absorbing passive region with a beam-guiding capability adjacent to an end face.

BACKGROUND OF THE INVENTION

A semiconductor laser comprises a body of material, generally including group III-V compounds or alloys of such compounds, having a thin active region between cladding regions of opposite conductivity type. Double heterostructure lasers, such as those disclosed by Botez in U.S. Pat. No. 4,347,486 and by Connolly et al. in U.S. patent application Ser. No. 367,212 filed Apr. 9, 1982, U.S. Pat. No. 4,461,008, which are incorporated herein by reference, are capable of producing a single transverse (the direction perpendicular to the plane of the layers) and lateral (the direction in the plane of the layers) and lateral (the direction perpendicular to the direction of light propagation) mode, high power laser beam. These lasers have a guide layer adjacent to the active layer so that light generated in the active layer propagates mostly in the adjacent guide layer, thereby producing a much larger emitting area. However, the emitting area is still small, typically on the order of several square micrometers (μm). The local power density is thus very high and may result in damage to the emitting end face which can be either catastrophic in nature or a slow, long term end face degradation.

To avoid either type of damage the output power density at the end face is held below the threshold at which such damage occurs. A transparent passivation coating, as disclosed by Ladany et al. in U.S. Pat. No. 4,178,564, incorporated herein by reference, may be placed on the emitting end face to increase the threshold at which the damage occurs. This combination of measures reduces the incidence of damage but the laser's inherent output power capability is not fully utilized.

Catastrophic damage may be caused by local heating of the end face to a temperature close to the melting temperature of the material by absorption of the laser light. To eliminate catastrophic damage and degradation, lasers have been fabricated in which the light absorbing active layer does not extend to the end face with a non-absorbing waveguide between the active layer and the end face, as disclosed, for example, by Botez in U.S. patent application Ser. No. 437,838 filed Oct. 29, 1982, U.S. Pat. No. 4,523,316, and incorporated herein by reference. Such devices have shown an increase in the threshold powers at which the long term and catastrophic damage occur of between about five and ten times.

Such devices do not, however, provide strong lateral mode control in the non-absorbing region adjacent to the end face. Thus, the lateral mode character of the output light beam will depend upon the length of the non-absorbing region which will differ from device to device because of the inaccuracy present in the cleav-
layer 32 and the end faces 14a and 14b. A burying region 40 overlies the mode control layer 38. An electrically insulating layer 42 overlies the cap layer 36 and the burying region 40 and has an opening 62 extending therethrough to the cap layer 36 over the mesa 20a. A high-conductivity, current-confinement zone 64 extends through the cap layer 36 and the second cladding region 34 towards the active layer 32. A first electrical contact 44 overlies the insulating layer 42 and contacts the cap layer 36 in the opening. A second electrical contact 46 overlies the second major surface 22.

FIG. 3 is a side view of a laser 80 with a light-transmissive coating 82 overlying the end face 14a through which laser light is emitted, as has been disclosed by Ladany et al. in U.S. Pat. No. 4,178,564. A light reflector 84 overlies the opposite end face 14b. Useful light reflectors include a metal as disclosed by Caplan et al. in U.S. Pat. No. 3,701,047 and a multilayer dielectric stack reflector as disclosed by Ettenberg in U.S. Pat. No. 4,092,659, both of which are incorporated herein by reference.

The bulk refractive index at the laser wavelength of the active layer 32 is greater than that of the guide layer 30 which, in turn, is greater than that of the cladding regions 28 and 34 and the burying region 40. The refractive index of the control layer 38 is between that of the first cladding region 28 and the burying region 40 and is preferably different from that of the guide layer 30. The combination of the active and guide layers 32 and 30 with the cladding regions 28 and 34 constitute an active region which has gain and provides a lateral and transverse optical index guide. The combination of the guide and control layers 30 and 38 together with the first cladding region 28 and the burying region 40 constitute a non-absorbing passive region which provides an optical index guide in the lateral and transverse directions.

The substrate 18, the buffer layer 26, the first cladding region 28 and the guide layer 30 are of one conductivity type. The second cladding region 34 and the cap layer 36 are of opposite conductivity type. The active layer 32 may be of either conductivity type and is typically only lightly conducting. The burying region 40 may be of either conductivity type and typically has a high resistivity which serves to block the flow of electrical current around the active region 32. Alternatively, the burying region 40 may be composed of two layers of opposite conductivity type with a reverse-biased P-N junction therebetween to block the current flow through the burying region 40 when a forward bias is applied to the laser 10.

If the current confinement zone 64 is present it has the same conductivity type as the second cladding region 34. The cap layer 36 may then have either the same or opposite conductivity type to that of the second cladding region 34. If it has the opposite conductivity type, the functions of the cap layer 36 and the insulating layer 42 may be combined, producing a current-blocking, reversed-biased P-N junction except over the mesa 20a when the laser is forward-biased.

The body 12 is composed of binary single-crystal III-V compounds and alloys thereof, such as GaAs and AlGaAs alloys, which are preferably lattice-matched to one another to within 0.5 percent.

The substrate 18 is composed of N-type GaAs having a major surface 20 which may be parallel to or, preferably, misoriented from a {100} crystallographic plane with the axis of the channels oriented parallel to a <110> crystalllographic axis. Use of a <110> direction is preferred since the end faces 14a and 14b are then cleavage planes. Preferably, the misorientation angle of the substrate surface with respect to the (001) plane is between about 5° and 45°, and optimally at about 15°. The tilt angle of the (001) plane from the major surface 20 is between about 0.2° and 1.5° and preferably about 0.7°.

The channels 24 are shown as having a dovetail shape which results from the channel axis being parallel to a <110> crystalllographic direction. The channels are formed using photolithographic and etching techniques as disclosed by Botez in U.S. Pat. No. 4,215,319, but may have a different shape, for example, a U, Vee or a rectangular shape. The channels 24 are typically between about 4 and 20 μm wide at the surface 20 and have a depth of about 4 μm, with a center-to-center spacing typically between about 20 and 45 μm. The height of the mesa 20a may be different from the height of the major surface 20 above the bottom of the channels 24 as disclosed by Botez in U.S. Pat. No. 4,426,701, incorporated herein by reference. This difference in height is typically between about 0.5 and 3 μm.

The various layers may be sequentially deposited using well-known liquid-phase epitaxy techniques, such as are described by Botez in U.S. Pat. No. 4,215,319 and by H. F. Lockwood et al. in U.S. Pat. No. 3,753,801, both of which are incorporated herein by reference. In liquid-phase epitaxy the local growth rate of a layer varies with the local curvature of the surface on which it is grown. The greater the amount of local positive curvature of the surface, when viewed from the direction of the overlying layers, the higher the local growth rate will be. For example, the first cladding region 28 may be grown to a thickness such that its surface, upon which the guide layer 30 is deposited, has a local depression over the mesa 20a. The guide layer 30 will then have a higher local growth rate over the convex portions at the corners of this depression. The top surface of the guide layer 30 will have a convex portion centered over the mesa 20a. The growth rate of the active layer 32 or the control layer 38 will be highest over this convex portion. The result is that the guide layer 30 tapers in increasing thickness in the lateral direction from the optical axis while the active and control layers 32 and 38 taper in decreasing thickness in the lateral direction from the optical axis.

The buffer layer 26, if present, is GaAs and is between about 1 and 3 μm thick over the mesa 20a. The first cladding region 28 is AlGa1−xAl where the fractional concentration w of Al is between about 0.25 and about 0.4 and is typically about 0.35 and is typically between about 1 and 3 μm thick over the mesa 20a. The guide layer 30 is AlGa1−xAs where the fractional concentration x of Al is less than that of the first cladding region 28 and greater than that in the active layer 32 and is typically between about 0.1 and 0.3 but preferably about 0.15. This layer tapers in increasing thickness from the portion thereof over the centerline of the mesa 20a and has a thickness over the mesa 20a between about 0.5 and about 2 μm.

The active layer 32 is AlGa1−xAs where the fractional concentration y of Al is less than in the guide layer 30 and is typically between about 0 and about 0.07. This layer is typically between about 0.05 and 0.25 μm thick over the mesa 20a, tapers in decreasing thickness in the lateral direction from the optical axis. This layer typically extends a distance of between about 100 and
ical formulae are concentrations by volume. The active
ation is then undersaturated which causes the active
active layer
to dissolve. This technique is preferred since it
ration temperature by between 0.5" and 2"
active chemical etching. The GaAs cap layer
entire surface of the guide layer
between about 0.05 and 1
control layer
and the cap layer
optical axis. It is to be understood that the tapers of the lateral
tapers of the active, guide and mode control
transverse direction will be. Preferably the mode con-
trol layer and the guide layer a W-shaped waveguide over the mesa is
form a weak positive index waveguide Journal of Quantum Electronics, QE-17, 78 (1981). In
the active region where the active layer overlies the
guide layer a W-shaped waveguide over the mesa is
formed by the combination of a higher index active
layer which decreases in thickness in the lateral direc-
tion and the guide layer which increases in thickness in
the lateral direction. This index guide which confines
the propagating laser beam in the lateral direction in
the active region.

Botez in U.S. patent application Ser. No. 437,838 has
disclosed a laser including a passive region adjacent the
emitting end face which includes only a guide layer
which tapers in increasing thickness in the lateral direc-
This structure produces an anti-guide or negative-
index waveguide without gain, i.e., the transverse effec-
tive refractive index only increases in the lateral direc-
tion, which is leaky and permits the propagating beam
to disperse. The mode control layer of the present in-
vention together with the guide layer produces a posi-
tive index guide which confines the propagating beam
in the lateral direction over the mesa in the passive
region and strongly reduces the leakage loss.

While the invention has been described in terms of
lateral tapers of the active, guide and mode control
layers induced by growth over a pair of channels, it is to
be understood that the invention includes any laser
having the required region 34 and the cap layer 36 are sequentially deposited over the
entire surface of the guide layer 30 using liquid-phase
epitaxy. Portions of these layers adjacent one or both of
the end faces are then removed by masking and selec-
tive chemical etching. The GaAs cap layer 36 may be
removed using an etchant such as: 1 H2SO4:8 H2O:8 H2O or 20 H2O:1 NH4OH at 20° C. for about 15
seconds. The AlGaAs second cladding region 34 may be
removed using as an etchant either 1 H2:1 H2O or 1
HCl:1 H2O. The relative concentrations in these chem-
ical formulae are concentrations by volume. The active
layer 32 is preferably removed by melt-etching by expo-
sure to an AlGa1-xAs solution where c is about 0.30
and increasing the temperature above the solution satu-
ration temperature by between 0.5° and 2° C. The solu-
tion is then undersaturated which causes the active
layer to dissolve. This technique is preferred since it
improves the nucleation during the regrowth of the
control layer 38. Alternatively, the AlGa1-xAs active
layer 32 where y is less than about 0.07, may be
removed using as an etchant 20 H2O:1 NH4OH. The
control layer 38 and the burying region 40 are grown
using standard liquid-phase epitaxy techniques. The
masking layer is then removed and the insulating layer
42 is deposited onto the cap layer 36 and the burying
region 40 by pyrolytic decomposition of silane in oxy-
gen or water vapor. The opening 60 preferably only extends over the cap
layer 36 and is formed through the insulating layer 42
using standard photolithographic masking techniques
and etching processes.

The first electrical contact 44 is composed of tita-
nium, platinum and gold deposited by vacuum evapora-
tion. The electrical contact 44 may be formed by vac-
uum deposition and sintering and gold, germanium and
nickel.

Lateral confinement of a propagating laser beam is
produced by an effective transverse refractive index
variation arising from the laterally varying thicknesses
and the different bulk refractive indices of the different
layers as disclosed, for example, by Botez in the IEEE
Journal of Quantum Electronics, QE-17, 78 (1981). In
the active region where the active layer overlies the
guide layer a W-shaped waveguide over the mesa is
formed by the combination of a higher index active
layer which decreases in thickness in the lateral direc-
tion and the guide layer which increases in thickness in
the lateral direction. This index guide which confines
the propagating laser beam in the lateral direction in
the active region.

A semiconductor laser incorporating the principles of
the invention was fabricated by sequential liquid-phase
epitaxy deposition onto the surface of an N⁺-GaAs
substrate wafer having a pair of dovetail-shaped chan-
nels with a 32 µm center-to-center spacing, a 12 µm
width and a 3.6 µm depth. The deposited layers were
an N-type AlGa1-xAs first cladding region 2.1 µm
thick; an N-type AlGa1-xAs guide layer 1.2 µm
thick; an N-type GaAs active layer 0.16 µm thick; a
P-type AlGa1-xAs second cladding region 1.2 µm
thick and a 0.67 µm P⁺-type GaAs cap layer. The
thicknesses are those over the center of the mesa be-
tween the channels. An etch-resistant SiO2 mask layer
was deposited on the cap layer and 50 μm wide openings with 300 μm center-to-center spacing transverse to the channel axis were formed therein. The exposed cap layer and second cladding regions were removed by chemical etching and the wafer re-inserted into the deposition apparatus. The GaAs active layer was removed by melt-etching and a v-type Al₀.₇₀Ga₀.₃₀As mode control layer 0.8 μm thick, a v-type Al₀.₃₀Ga₀.₇₀As burying region 1.1 μm thick and a P⁺-type GaAs cap layer 0.45 μm thick were deposited on the guide layer in the openings. The etch mask was stripped and a 0.1 μm thick SiO₂ layer having a 10 μm wide opening therethrough down to the cap layer was formed. A titanium-platinum-gold metal contact was deposited on the SiO₂ and the cap layer. A gold-germanium-nickel contact was made to the substrate. Individual laser chips were formed from the substrate wafer by cleaving through the burying region. A maximum output power of about 1.5 watts was obtained with 100 nanosecond pulses at a 1 kHz rate which is about four times more power than for devices of this type without the passive region. The solid curve in FIG. 4 shows the output power for a laser incorporating the mode control layer in the passive region while the broken curve shows the output power for a laser without the passive region. This maximum power is estimated to correspond to a catastrophic-bulk-damage power density threshold of 2–3×10⁸ W/cm². Similar power levels at 100-ns pulsed operation have been previously reported for lasers with a non-absorbing end face, but for non-mode-stabilized lasers of 15–20 μm-wide near-field spots. The linear power density at the emitting end face was between 150 and 200 milliwatts/μm, which is 2 to 3 times larger than for prior art devices having a non-absorbing passive region. We believe the main reason for this difference is the large transverse spot size in the passive regions, as evidenced by the very narrow transverse angular beamwidth angle of 15°. Fundamental mode operation is obtained to 80 milliwatts in an angular beamwidth of 7°.

I claim:

1. A semiconductor laser comprising:
   a body of material having a pair of opposed end faces which are reflective of light, at least one of which is partially transmissive of light to form a laser cavity having an optical axis extending between the end faces, said body including:
   a substrate having first and second opposed major surfaces;
   a first cladding region overlying said first major surface;
   a guide layer overlying the first cladding region and tapering in increasing thickness in the lateral direction from the optical axis;
   an active layer which tapers in decreasing thickness from the optical axis overlying a portion of the guide layer and spaced a distance from a first end face;
   a second cladding region overlying the active layer;
   a non-absorbing mode control layer which tapers in decreasing thickness in the lateral direction from the optical axis overlying the guide layer and extending between the active layer and said first end face;
   a burying region overlying the mode control layer; and
   first and second electrical contacts overlying said second cladding region and said second major surface respectively.

2. The laser of claim 1 wherein the active layer has a larger refractive index than the guide layer and the guide layer has a larger refractive index than the first and second cladding regions and the burying region.

3. The laser of claim 2 wherein the refractive index of the mode control layer is different from that of the guide layer.

4. The laser of claim 3 wherein the refractive index of the mode control layer is less than that of the guide layer.

5. The laser of claim 4 wherein the refractive index of the mode control layer is greater than that of the guide layer.

6. The laser of claim 3 wherein a cap layer overlaps the second cladding region and an electrically insulating layer having an opening therethrough, overlies the cap layer and the burying region and the first electrical contact overlies the electrically insulating layer and the cap layer in said opening.

7. The laser of claim 6 wherein the substrate and the cap layer are composed of GaAs, the first and second cladding regions, the guide and mode control layers and the burying region are composed of AlGaAs alloys.

8. The laser of claim 1 wherein the active layer is spaced a distance from both of the end faces and the mode control layer extends between the active layer and both end faces.

9. The laser of claim 1 wherein the mode control layer is thicker than the active layer along the optical axis.

10. A semiconductor laser comprising:
    a body of material having a pair of opposed end faces which are reflective of light, at least one of which is partially transmissive of light to form a laser cavity having an optical axis extending between the end faces, said body including:
    a substrate having first and second opposed major surfaces and having a pair of substantially parallel channels extending between the end faces with a mesa therebetween in the first surface;
    a first cladding region overlying said first major surface, the channels and the mesa;
    a guide layer overlying the first cladding region and tapering in increasing thickness in the lateral direction from the optical axis;
    an active layer which tapers in decreasing thickness from the optical axis overlying a portion of the guide layer and spaced a distance from a first end face;
    a second cladding region overlying the active layer;
    a mode control layer which tapers in decreasing thickness in the lateral direction from the optical axis overlying the guide layer and extending between the active layer and said first end face;
    a burying region overlying the mode control layer; and
    first and second electrical contacts overlying said second cladding region and said second major surface respectively.

11. The laser of claim 10 wherein the optical axis is over the center of the mesa.

12. The laser of claim 11 wherein the active layer has a larger refractive index than the guide layer and the guide layer has a larger refractive index than the first and second cladding regions and the burying region.
13. The laser of claim 12 wherein the refractive index of the mode control layer is different from that of the guide layer.

14. The laser of claim 13 wherein the refractive index of the mode control layer is less than that of the guide layer.

15. The laser of claim 13 wherein the refractive index of the mode control layer is greater than that of the guide layer.

16. The laser of claim 13 wherein a cap layer overlies the second cladding region and an electrically insulating layer having an opening therethrough, overlies the cap layer and the burying region and the first electrical contact overlies the electrically insulating layer and the cap layer in said opening.

17. The laser of claim 16 wherein the substrate and the cap layer are composed of GaAs, the first and second cladding regions, the guide and mode control layers and the burying region are composed of AlGaAs alloys.

18. The laser of claim 11 wherein the active layer is spaced a distance from both of the end faces and the mode control layer extends between the active layer and both end faces.

19. The laser of claim 10 wherein the mode control layer is thicker than the active layer along the optical axis.

20. A semiconductor laser comprising:
   a body of material having a pair of opposed end faces which are reflective of light, at least one of which is partially transmissive of light to form a laser cavity having an optical axis extending between the end faces, said body including:
   a substrate having first and second opposed major surfaces;
   a first cladding region overlying said first major surface;
   a guide layer overlying the first cladding region;
   an active layer overlying a portion of the guide layer and spaced a distance from a first end face;
   a second cladding region overlying the active layer;
   a mode control layer, which is nonabsorbing at wavelength of the emitted laser light, overlying the guide layer and extending between the active layer and said first end face;
   a burying region overlying the mode control layer; and
   first and second electrical contacts overlying said second cladding region and said second major surface respectively wherein the active layer has a larger refractive index than the guide layer and the guide layer has a larger refractive index than the first and second cladding regions and the burying region; and wherein the refractive index of the mode control layer is different from that of the guide layer and is larger than the refractive indices of the cladding regions and the burying region.

21. The laser of claim 20 wherein the refractive index of the mode control layer is less than that of the guide layer.

22. The laser of claim 21 wherein the first and second cladding regions, the guide and mode control layers and the burying region are composed of AlGaAs alloys with the aluminum concentration in the mode control layer being greater than the aluminum concentration in the guide layer.

23. The laser of claim 20 wherein the refractive index of the mode control layer is greater than that of the guide layer.

24. The laser of claim 23 wherein the first and second cladding regions, the guide and mode control layers and the burying regions are composed of AlGaAs alloys with the aluminum concentration in the mode control layer being less than the aluminum concentration in the guide layer.