Symmetric quantum dots are embedded in quantum wells. The symmetry is achieved by using slightly off-axis substrates and/or overpressure during the quantum dot growth. The quantum dot structure can be used in a variety of applications, including semiconductor lasers.

16 Claims, 9 Drawing Sheets
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FIG. 3A

FIG. 3B
<table>
<thead>
<tr>
<th>Ref.</th>
<th>Layer</th>
<th>Material</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>750</td>
<td>Cap</td>
<td>InGaAs (Lattice Matched to InP), p Doped 1.5E19</td>
<td>100 nm</td>
</tr>
<tr>
<td>747</td>
<td>Grading</td>
<td>AlGaInAs (Lattice Matched to InP), p Doped 5E17-1.5E19</td>
<td>20 nm</td>
</tr>
<tr>
<td>745</td>
<td>Cladding</td>
<td>AlInAs (Lattice Matched to InP), p Doped 5E17</td>
<td>1100 nm</td>
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<tr>
<td>745</td>
<td>Cladding</td>
<td>AlInAs (Lattice Matched to InP), p Doped 1E17</td>
<td>400 nm</td>
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<tr>
<td>740</td>
<td>Waveguiding</td>
<td>Al&lt;sub&gt;30&lt;/sub&gt;Ga&lt;sub&gt;18&lt;/sub&gt;In&lt;sub&gt;52&lt;/sub&gt;As</td>
<td>105 nm</td>
</tr>
<tr>
<td>735</td>
<td>Barrier</td>
<td>Al&lt;sub&gt;28&lt;/sub&gt;Ga&lt;sub&gt;22&lt;/sub&gt;In&lt;sub&gt;50&lt;/sub&gt;As</td>
<td>15 nm</td>
</tr>
<tr>
<td>730</td>
<td>Top Quantum Well</td>
<td>Al&lt;sub&gt;20&lt;/sub&gt;Ga&lt;sub&gt;16&lt;/sub&gt;In&lt;sub&gt;64&lt;/sub&gt;As</td>
<td>6.3 nm</td>
</tr>
<tr>
<td>725</td>
<td>Quantum Dots</td>
<td>InAs</td>
<td>4.0 Monolayers</td>
</tr>
<tr>
<td>720</td>
<td>Bottom Quantum Well</td>
<td>Al&lt;sub&gt;20&lt;/sub&gt;Ga&lt;sub&gt;16&lt;/sub&gt;In&lt;sub&gt;64&lt;/sub&gt;As</td>
<td>1.3 nm</td>
</tr>
<tr>
<td>715</td>
<td>Barrier</td>
<td>Al&lt;sub&gt;28&lt;/sub&gt;Ga&lt;sub&gt;22&lt;/sub&gt;In&lt;sub&gt;50&lt;/sub&gt;As</td>
<td>15 nm</td>
</tr>
<tr>
<td>710</td>
<td>Waveguiding</td>
<td>Al&lt;sub&gt;30&lt;/sub&gt;Ga&lt;sub&gt;18&lt;/sub&gt;In&lt;sub&gt;52&lt;/sub&gt;As</td>
<td>105 nm</td>
</tr>
<tr>
<td>705</td>
<td>Cladding</td>
<td>AlInAs (Lattice Matched to InP), n Doped 1E17</td>
<td>500 nm</td>
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<tr>
<td>704</td>
<td>Graded Interface</td>
<td>AlGaInAs (Lattice Matched to InP), n Doped 1E18</td>
<td>20 nm</td>
</tr>
<tr>
<td>702</td>
<td>Substrate</td>
<td>InP, n Doped, (100) Misoriented +/-3° (111)B</td>
<td></td>
</tr>
</tbody>
</table>

**FIG. 4**
[1-10] Arsenic Rich 2x1 Reconstruction

 arsenic Stable/Rich 2x4

Symmetric and Asymmetric Quantum Dots

Asymmetric Quantum Dots

FIG. 6A

FIG. 6B
Arsenic Rich 2x1 Reconstruction

Symmetric Quantum Dots

FIG. 7
QUANTUM DOT STRUCTURES

CROSS-REFERENCE TO RELATED APPLICATION


BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to semiconductor quantum dot structures and devices.

2. Description of the Related Art

A semiconductor quantum dot is a structure having energy barriers that provide quantum confinement of electrons and holes in three dimensions. Because of these properties, there is interest in using quantum dot structures in a variety of electronic and optoelectronic devices. For example, studies indicate that quantum dot lasers can potentially perform better than conventional quantum well lasers in many respects. A quantum dot laser can have a lower fill factor (i.e., volume of material to be pumped) and/or an improved density of states function compared to a quantum well laser. Studies also indicate that the threshold current of a semiconductor laser may be improved by using quantum dot active regions, due to the smaller volume of material and reduced number of states.

Quantum dot lasers emitting light in the 1.3 to 1.6 micron wavelength range are particularly interesting for fiber optic communication systems. In particular, there has been interest in using InAs quantum dots as the active region for semiconductor lasers. Conventional approaches to creating InAs quantum dots are typically based on spontaneous processes that occur when growing strained on GaAs or InP substrates. Unfortunately, these conventional approaches have significant drawbacks that limit the usefulness of the resulting quantum dot structures, particularly in the 1.3 to 1.6 micron wavelength range.

For example, one important challenge is controlling the shape of the quantum dot. Usually, a high degree of symmetry in the shape of the quantum dot is desirable. For instance, a spherical quantum dot results in isotropic optical properties that can be important in certain optoelectronic applications. However, conventional approaches have not been able to produce symmetric InAs quantum dots on an InP substrate in a manner that is useful for optoelectronic devices. Instead, the resulting quantum dots are elongated in shape and generally referred to as quantum dashes. The resulting devices are highly anisotropic and the lack of symmetry limits the device performance. Attempts to create more symmetric InAs quantum dots have resulted in inadequate device properties, such as high threshold current, low modal gain and strong temperature dependence. These deficiencies are believed to be caused by a failure to achieve the desired shape and/or density for the InAs quantum dots.

Thus, there is a need to create improved quantum dot structures.

SUMMARY OF THE INVENTION

One aspect of the present invention overcomes the limitations of the prior art by fabricating more symmetric quantum dots embedded in a quantum well. In one approach, the symmetry is achieved by using slightly off-axis substrates and/or overpressure during the quantum dot formation.

For example, in one implementation, InAs quantum dots are embedded in an AlGaNAs quantum well and the substrate is a slightly off-axis (100) InP substrate (e.g., misoriented towards either the (110) or (111) directions). The growth conditions for the InAs quantum dots include an As overpressure of between two and five. The resulting InAs quantum dots have a mean height of between 2 and 5 nm, a mean width of between 15 and 25 nm, and a mean length-to-width ratio of between 1:1 and 3:1.

Other aspects of the invention include various devices based on these structures and methods for operating these structures. For example, in one embodiment, the quantum dot structures are used as the active region of a semiconductor laser with a lateral laser cavity. For slightly off-axis (100) InP substrates that are misoriented towards the (110) or (111) directions, the lateral laser cavity preferably is aligned to the (011) or (01T) directions, respectively.

BRIEF DESCRIPTION OF THE DRAWING

The invention has other advantages and features which will be more readily apparent from the following detailed description of the invention and the appended claims, when taken in conjunction with the accompanying drawing, in which:

FIG. 1A is a perspective view of a core region of quantum dots.

FIG. 1B is a side view showing an embedded quantum dot.

FIG. 1C is a side view showing a quantum dot embedded in a quantum well.

FIGS. 2A-2C are perspective views illustrating some of the steps used to form a quantum dot laser.

FIGS. 3A-3B are side views illustrating growth sequences for embedding quantum dots.

FIG. 4 is a side view illustrating an example growth sequence for a quantum dot laser.

FIG. 5 shows crystallographic planes for a slightly off-axis (100) InP substrate.

FIGS. 6A-6B are atomic force micrographs showing the statical dependence with arsenic pressure for an on-axis (100) InP substrate.

FIG. 7 is an atomic force micrograph of arsenic rich InAs for a slightly off-axis InP substrate.

FIG. 8 is a perspective view of a semiconductor laser with a quantum dot active region.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1A is a perspective view illustrating the dimensions of one example of a core region with quantum dots. The quantum dots 205 have a mean height h, width w and length l. In one embodiment, each of the three dimensions (h, w, and l) of the quantum dot is selected to be less than the room temperature thermal de Broglie wavelength. In the example of FIG. 1A, the quantum dots 205A-205C are depicted spaced apart mesas formed on a semiconductor substrate 210. However, in other embodiments, the quantum dots 205 can take shapes other than rectangular mesas.

As shown in the side view of FIG. 1B, in this example, an underlying layer (or layers) 215 is first formed on a substrate 210. The quantum dots 205 are embedded in an embedding
layer 220. Additional layer(s) 225 may also be grown. As shown in the side view of FIG. 1C, in one embodiment, the quantum dots 205 are formed in quantum wells having a bottom barrier layer 290, first and second quantum well layers 280, 285, and a top barrier layer 295. The material composition of the layers is preferably selected so that thick layers are lattice matched or nearly lattice matched (e.g., less than the critical thickness for dislocation formation) to prevent the formation of misfit dislocations. However, the quantum dots and individual layers may be pseudomorphic strained layers.

Referring again to FIG. 1A, the height of the quantum dots 205 is measured in a direction perpendicular to the plane of the substrate 210, along a z-axis corresponding to the direction of growth. Thus, the height h may also be referred to as the thickness of a layer. For example, layers that are grown in the z direction are commonly described by a growth thickness. The length and width of the quantum dots 205 are measured in x and y directions parallel to the growth plane (i.e., a plane parallel to the plane of the substrate).

In one embodiment, the quantum dots are typically 2-12 nm high and 10-30 nm wide (in each direction). The height h of each quantum dot preferably is equal to or less than its width, and the quantum dots preferably are not elongated and maintain a mean length-to-width ratio in the range of 1:1 to 1:3. The distribution of the size and shape of the quantum dots preferably is also selected so that the quantum dots have a ground state energy level that saturates at room temperature and have a sequence of excited states that have an energy level separation that facilitates forming a high, broad optical gain spectrum. In a preferred embodiment, the quantum dots are fabricated as self-assembled structures (sometimes also known as "self-organized structures") in a III-V compound semiconductor materials system. In these materials systems, examples of the group III element include Al, Ga and In and examples of the group V element include N, P, As and Sb. Many different III-V semiconductor alloy compositions can be used, based on the known relationships between bandgap energy and lattice constant of different III-V compounds. GaAs and InP are the most commonly used III-V compound semiconductor substrates, although other types of substrates may also be used as well.

A variety of crystal growth techniques may also be used. Typically, the growth technique will have sufficient surface kinetic reactions (e.g., surface ad-atom or molecular migration) to favor island growth in response to the growth of a higher lattice constant material upon a lower lattice constant material. Examples of suitable growth techniques include molecular beam epitaxy (MBE); gas source MBE (GSMBE) and metallo-organic chemical vapor deposition (MOCVD).

FIGS. 2A-2C illustrate some aspects of the fabrication of self-assembled quantum dots according to the invention. In FIG. 2A, the semiconductor substrate 302 is a slightly off-axis substrate (as will be further described below). The vicinal substrate 302 has a staircase shape with ledges/terraces that facilitate island growth. Ignoring layers 304-308 for the moment, a substantially planar III-V compound semiconductor support layer 310 is grown. For example, if substrate 302 is InP, then support layer 310 might be AlGaNAs or InGaAsP. The support layer 310 may be grown either directly on the substrate 302 or upon other layers previously grown on the substrate. In the embodiment of FIG. 2A, the support layer 310 is part of a quantum well grown on an underlying barrier layer 308, a waveguide layer 306, and a cladding layer 304. In one embodiment, the growth parameters of the support layer 310 are selected to achieve a mean surface roughness of less than 0.3 nm.

Referring to FIG. 2B, growth parameters are selected to form self-assembled islands 320 during deposition of a compound semiconductor on the support layer 310. The deposited compound semiconductor 320 has a lower bandgap than the support layer 310 and also has a larger relaxed lattice constant than the underlying layer 310 (e.g., InAs quantum dots grown on AlGaNAs). In particular, the lattice mismatch of the lower bandgap semiconductor 320 is preferably selected to be at least about 1.8% greater than the underlying semiconductor layer 310 to produce a Stranski-Krastanow (S-K) growth mode. In the S-K growth mode, the driving force for the formation of islands is the reduction in strain energy afforded by elastic deformation, i.e., for S-K growth it is more energetically favorable to increase surface energy by islanding than by relaxing strain by dislocation generation. In a S-K growth mode, the growth becomes three dimensional after a critical thickness of the larger lattice constant material is grown upon an initial wetting layer 325.

In this case, selection of the growth parameters controls the height and the length-to-width ratio of the islands to form more symmetric quantum dots. In particular, overpressure of the group V element is applied during growth of the semiconductor 320, resulting in quantum dots with a length-to-width ratio of not more than 3:1. One advantage of this technique is that more symmetric quantum dots can be grown, even for systems with lower strains.

As shown in FIG. 2B, each island 320 is a quantum dot that has a nominal height, width and length. The islands tend to be aligned along a preferred crystal orientation. A residual wetting layer 325 may remain on the surface of well portion 310. After the self-assembled islands are formed, they are embedded in a higher bandgap material 330 (e.g., a layer of AlGaNAs or InGaAsP), as shown in FIG. 2C. Factors such as interdiffusion, phase segregation, and spinodal decomposition during the embedding process preferably are taken into account because they may affect the shape and composition of the quantum dots. In one embodiment, the quantum dots 320 are embedded in the remainder 330 of the quantum well, followed by another barrier layer 335, waveguide layer 340, cladding layer 345, and cap layer 350. Each quantum dot thus consists of an island of low bandgap material surrounded on all sides by a higher bandgap material. The island formation process can be repeated to form additional layers of quantum dots.

As previously described, the quantum dots may be embedded in quantum wells. The composition of the quantum well layer may be lattice matched to the substrate or strained up to the critical thickness for the generation of misfit dislocations. The as-grown islands may vary significantly in height. For quantum dots embedded in quantum wells, it is usually desirable that the islands be completely embedded in the quantum wells. Several techniques may be used to achieve this.

In the approach of FIG. 3A, the quantum dots 520 are embedded between a lower quantum well layer 510 having a thickness of d1 and an upper quantum well layer 530 having a thickness of d2, with d2>d1. In the example of FIG. 3A, the quantum well layers 510, 530 are located between barrier layers 508, 535 that have a bandgap energy larger than that of the quantum well layers. The upper quantum well layer 530 is thick enough so that it covers all of the quantum dots 520. Thus, the quantum dots 520 are embedded in the quantum well 510, 530 despite variances in the height of the quantum dots.
In FIG. 3B, growth parameters are adjusted to trim the quantum dots. In this case, quantum dots 520 are grown and a top quantum well layer 530 is grown. The thickness of the top quantum well layer 530 may be selected to be less than the height of the as-grown InAs islands 520. A thermal desorption (evaporation) step is performed after the growth of quantum well layer 530 to remove any uncovered portions of the InAs dots 520, as indicated in phantom. Thus, the peaks of the quantum dots 520 are trimmed and the quantum dots are embedded in the quantum well 510, 530. FIG. 4 shows the layer structure for one example of a quantum dot laser. A preferred fabrication technique for this structure is MBE, although other techniques may be used as well. This structure is fabricated as follows. The substrate 702 is a slightly off-axis n-type InP substrate. In particular, InP single crystal misoriented (100) substrates ranging from 1-5 degrees toward the (111)B or (110) plane are preferred. Crystallographic planes for the misoriented (100) substrate are shown in FIG. 5. The InP substrate is preferably cleaned in ultra-high vacuum prior to growth, by heating the substrate to 545°C under an 8x10^-4 mbar (mbur) beam equivalent pressure (BEP).

An n-type AlInAs optical cladding layer 705 is grown that is closely lattice matched to the InP substrate 702. In one embodiment, a graded interface layer 704 is included between substrate 702 and layer 705 to reduce electrical resistance. An AlGaInAs waveguiding layer 710 having an energy bandgap of 1.03 eV is then grown. The AlGaInAs waveguiding layer 710 preferably has a thickness of between about 100 nm to 500 nm.

An AlGaInAs quantum well barrier layer 715 is then grown having a composition corresponding to a bandgap energy of 1.03 eV. In one embodiment, the barrier layer is an Al0.28Ga0.72In0.50As layer having a thickness of about 15 nm. A bottom quantum well layer 720 is then grown. In one embodiment, this quantum well layer includes a 1.3 nm layer of Al0.5Ga0.45In0.64As having a semiconductor bandgap energy of 0.95 eV.

A preselected nominal InAs layer thickness 725 is then grown having a sufficient number of monolayers (four in this example) of InAs to form islands. In one embodiment, the substrate temperature is between 490 and 510 degrees Celsius as measured by a pyrometer and the As overpressure is two to five times that of the In. These growth parameters appear to result in an intermediate transition between a 2x4 (i.e., As rich) and a 4x2 (i.e., metal rich) reconstruction, thus yielding more symmetrical quantum dots. The resulting arsenic-rich 2x1 quantum dots are typically 2 to 5 nm high and 15 to 25 nm in length and width. The dot density is in the range of 2-5x10/square cm. An increased growth temperature tends to result in a more uniform distribution of dot sizes. Conversely, an increase in growth rate tends to reduce the uniformity of the dot size.

A top quantum well layer 730 is then grown to embed the islands. In one embodiment, the second quantum well layer is a 6.3 nm layer of Al0.3Ga0.67In0.64As having a semiconductor bandgap energy of 0.95 eV. More generally, quantum well layers 720, 730 with 18-22% Al and 14-18% Ga are generally preferred. Another barrier layer 735 is then grown. In one embodiment, this barrier layer is 15 nm of Al0.28Ga0.72In0.50As. Multiple layers of embedded quantum dots may be formed by repeating the growth sequence of layers 715, 720, 725, 730, 735. In this example, the sequence of layers 715, 720, 725, 730, and 735 is repeated five times.

A second waveguiding layer 740, such as an Al0.3Ga0.67In0.64As layer may then be grown. A p-type optical cladding layer 745 of AlGaAs is then grown. A highly p-doped cap layer 750 may then be grown to facilitate forming high quality ohmic contacts to diode laser structure. A grading composition p-type layer 747 may be included to further reduce contact resistance.

The refractive indices of the optical cladding layers 705 and 745 and the waveguiding layers 710 and 740 are preferably selected to achieve significant optical confinement in cavity lasers formed from the material. Empirical and theoretical techniques to select optical cladding and waveguiding compositions and thicknesses are well known in the art.

Returning to the quantum dot layer, note that the surface reconstruction of lattice matched Ga0.3Ga0.7In0.64As under As stable conditions is a highly anisotropic 2x4 reconstruction. Under these growth conditions, the resulting InAs quantum dots are highly elongated, as shown in FIG. 6A. Increasing the arsenic overpressure beyond the arsenic stable anisotropic 2x4 reconstruction to a more symmetric 2x1 surface reconstruction increases the symmetry of the InAs dot shape. This typically requires an As overpressure of greater than 6x10^-4 mbar. Atomic force micrographs showing the spatial dependence with arsenic pressure on (100) InP are shown in FIGS. 6A-6D.

FIG. 7 is an atomic force micrograph of the arsenic rich InAs on greater than (100) 2 degrees towards (111)B on InP substrate. The sheet density is greater than 5x10/cm2. The growth techniques and resulting quantum dot structures described above have significant advantages. For example, the resulting quantum dot structure results in a significantly higher density of quantum dots compared to conventional processing of on-axis (100) InP substrates. The use of slightly off-axis (100) substrates, as compared to high index InP substrates (e.g., highly off-axis substrates such as (311) substrates), also avoids difficulties materials problem from the standpoint of processing laser facets. For example, the use of slightly off-axis (100) substrates can avoid the high threshold currents from large mirror losses that can be present in lasers based on highly off-axis (311) substrates. Additionally, high index substrates energetically promote misfit dislocations in the InAs layer.

The growth techniques described above are not limited to the specific structures or materials systems shown. For example, the techniques generally work well with low strain systems (e.g., in the range of 3-7% strain) and, just as importantly, many other fabrication techniques do not work well with these low strain systems. Therefore, these growth techniques may be applied to other materials systems with similar strains. Examples of such systems include those based on Sb or Te. Thus, similar techniques may be used to form InSb quantum dots on GaSb substrates, for example.

The different growth techniques may also be used separately, rather than always in combination. For example, slightly off-axis substrates can be used without Group V overpressure and vice versa.

The quantum dot structures were described above in the context of a semiconductor laser. They can be used in the active regions of a variety of optoelectronic devices, such as optical amplifiers, discrete lasers, tunable lasers, and monolithic arrays of lasers. Quantum dots can be included in the active region of a p-i-n laser diode structure that includes an optical waveguide structure to provide optical confinement. Quantum dots can also be used in other applications as well (e.g., electronics). The quantum dot growth techniques described above can be used to fabricate quantum dots for a wide-range of devices and based on quantum dots of various shapes, sizes and dot densities. In a preferred embodiment,
the quantum dots are self-assembled quantum dots with a length-to-width ratio of no more than three.

As examples of some devices where quantum dots can be used, referring to U.S. Pat. No. 6,600,169, "Quantum Dush Devices," filed Sep. 20, 2001 and issued on Jul. 29, 2003, the quantum dot regions described above can be used as the active layer in the ridge laser of FIG. 9, the tunable external cavity lasers of FIGS. 15-16, the DBR lasers of FIGS. 17-18, the multi-wavelength laser arrays of FIG. 19, the VCSEL of FIG. 20 and/or the transistors of FIGS. 20-21.


As a specific example, consider the semiconductor laser shown in FIG. 8. This laser has a lateral laser cavity 810 (as opposed to a vertical laser cavity as can be found in VCSELS). The lateral laser cavity 810 is oriented in the plane of the substrate (i.e., primarily in the x-y plane). Edge emitting lasers, including those based on cleaved facets, and DBR and DBR lasers are some examples of semiconductor lasers that have lateral laser cavities. In FIG. 8, the laser cavity is shown in cross section. A quantum dot structure 820, such as those described above, provides optical gain for the laser cavity.

If the quantum dots in structure 820 exhibit some asymmetry (e.g., they are elongated in one direction), then the laser cavity 810 preferably is oriented so that the electric field of a TE polarized wave in the laser cavity is aligned with the elongated direction of the quantum dots. For example, for a nominal (100) InP substrate that is tilted 2 degrees towards the (110) direction, the lateral laser cavity 810 preferably is aligned with the (011) direction of the substrate. For a nominal (100) InP substrate that is tilted 3 degrees towards the (111)$_{B}$ direction, the lateral laser cavity 810 preferably is aligned with the (011) direction of the substrate. Even if perfectly symmetric quantum dots are expected, it can be advantageous to orient the laser cavity in these directions just in case some unexpected asymmetry appears. Orienting the lateral laser cavity in this manner typically results in lower threshold current, higher optical gain and/or better temperature performance.

What is claimed is:

1. A semiconductor active region for providing gain comprising:
a quantum well formed on a slightly off-axis substrate; and
a plurality of quantum dots embedded in the quantum well, wherein each quantum dot has a length-to-width ratio of less than three.

2. The semiconductor active region of claim 1 wherein:
the quantum well is an AlGaInAs quantum well; and
the quantum dots comprise InAs quantum dots having a thickness less than a thickness of the quantum well.

3. The semiconductor active region of claim 1 wherein the crystallographic orientation of (100) is misoriented toward one of the family of (110) directions.

4. The semiconductor active region of claim 1 wherein the crystallographic orientation of (100) is misoriented toward one of the family of (111) directions.

5. The semiconductor active region of claim 1 wherein the quantum dots have a size distribution and a sequence of quantum confined energy states selected to form a continuous optical gain spectrum.

6. The semiconductor active region of claim 1 wherein the quantum dots have a mean height of between 2 and 5 nm, a mean width of between 15 and 25 nm, a mean length of between 15 and 25 nm and a mean length-to-width ratio of between 1:1 and 3:1.

7. The semiconductor active region of claim 1 wherein the quantum dots have a relaxed lattice constant that is not more than 7% greater than the substrate.

8. A semiconductor laser comprising:
an active region comprising:
a quantum well formed on a slightly off-axis substrate; and
a plurality of quantum dots embedded in the quantum well, wherein asymmetry in the quantum dots is characterized by an elongated direction; and
a lateral laser cavity including the active region, wherein the lateral laser cavity is oriented so that an electric field of a TE polarized wave in the lateral laser cavity is aligned with the elongated direction.

9. The semiconductor laser of claim 8 wherein:
the slightly off-axis substrate is a nominal (100) InP substrate that is tilted towards the (110) direction; and
the lateral laser cavity is aligned with the (011) direction of the substrate.

10. The semiconductor laser of claim 8 wherein:
the slightly off-axis substrate is a nominal (100) InP substrate that is tilted towards the (111)$_{B}$ direction; and
the lateral laser cavity is aligned with the (011) direction of the substrate.

11. A semiconductor active region for providing gain comprising:
a quantum well formed on a slightly off-axis substrate; and
a plurality of quantum dots embedded in the quantum well, wherein each quantum dot has a length-to-width ratio and the plurality of quantum dots have a mean length-to-width ratio of less than three; wherein the quantum dots have a size distribution and a sequence of quantum confined energy states selected to form a continuous optical gain spectrum.

12. The semiconductor active region of claim 11 wherein
the quantum dots have a mean height of between 2 and 5 nm, a mean width of between 15 and 25 nm, a mean length of between 15 and 25 nm and a mean length-to-width ratio of between 1:1 and 3:1.

13. The semiconductor active region of claim 11 wherein
the quantum dots have a relaxed lattice constant that is not more than 7% greater than the substrate.

14. The semiconductor active region of claim 11 wherein:
the slightly off-axis substrate is an InP substrate; the quantum well is an AlGaInAs quantum well; and
the quantum dots comprise InAs quantum dots having a thickness less than a thickness of the quantum well.

15. The semiconductor active region of claim 11 wherein
the slightly off-axis substrate is an InP with a crystallographic orientation of (100) misoriented toward one of the family of (110) directions.

16. The semiconductor active region of claim 11 wherein
the slightly off-axis substrate is an InP with a crystallographic orientation of (100) misoriented toward one of the family of (111) directions.