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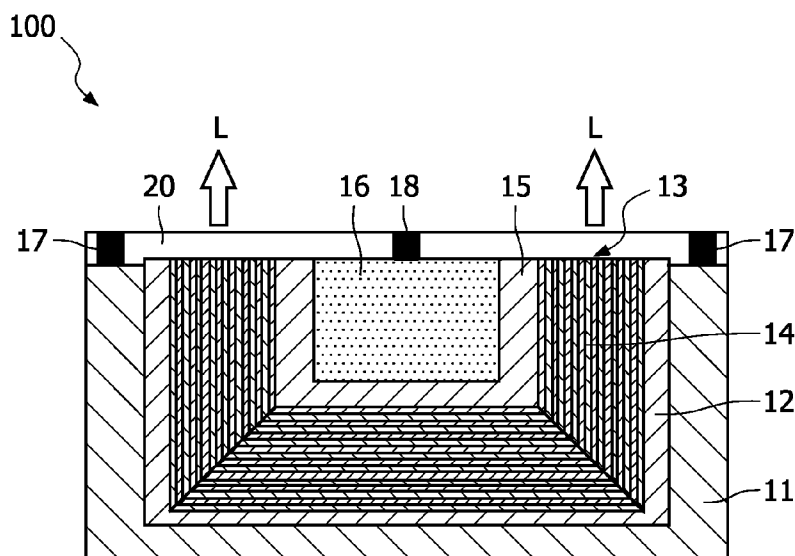
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[Continued on next page]

(54) Title: QUANTUM CASCADE SURFACE EMITTING SEMICONDUCTOR LASER DEVICE AND METHOD OF MANUFACTURING A SEMICONDUCTOR LASER DEVICE



(57) Abstract: The invention provides a quantum cascade laser device (100, 101) in a semiconductor substrate (11), which quantum cascade laser device (100, 101) comprises a plurality of semiconductor layers (14) having a side surface (13) that exposes a side of each semiconductor layer. The quantum cascade laser device (100, 101) emits a light beam (L) in a direction substantially perpendicular to the side surface (13) of the quantum cascade laser device (100, 101), which side surface (13) is essentially parallel to a top surface of the semiconductor substrate (11). The power loss of the quantum cascade laser device (100, 101) is reduced considerably, because the light beam (L) is not diffracted or reflected before it is emitted from the quantum cascade laser device (100, 101), which improves the power efficiency of the quantum cascade laser device (100, 101). The invention further provides a method of manufacturing such a quantum cascade laser device (100, 101).

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- as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))
- as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))
- before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments

Published:

- with international search report

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SEMICONDUCTOR LASER DEVICE AND METHOD OF MANUFACTURING A SEMICONDUCTOR LASER DEVICE

The invention relates to a semiconductor laser device and method of manufacturing a semiconductor laser device.

5 There are a variety of types of semiconductor laser devices, such as diode lasers (bipolar) and non-diode lasers such as, for example, quantum cascade lasers (unipolar, i.e. based on one type of carrier typically electrons in the conduction band). Diode lasers comprise active region materials of which the bandgap essentially determines, and limits, the lasing wavelength. Unlike diode lasers, the lasing wavelength of a quantum cascade laser is
10 essentially determined by quantum confinement, i.e. by the thickness of the layers of active regions, rather than by the bandgap of active region material. Additionally, semiconductor laser devices may be edge-emitting or surface-emitting lasers (SELs). Edge-emitting semiconductor lasers output their radiation parallel to the wafer or substrate surface, while in SELs, the radiation is output perpendicular to the wafer or substrate surface. One type of SEL
15 is the vertical cavity surface emitting laser (VCSEL). The VCSEL structure usually consists of an active (gain) region sandwiched between two distributed Bragg reflector (DBR, or stack) mirrors. Other types of VCSELs sandwich the active region between metal mirrors.

 The known quantum cascade lasers comprise a multiplicity of identical units, each unit comprising an active region and an injector/relaxation region. An upper and at least
20 one lower energy level is associated with each active region. Under an applied field, charge carriers (typically electrons) migrate from a lower energy level of a given active region through an injector/relaxation region to the upper energy level of the adjacent downstream active region, followed by a radiative transition from the upper level to a lower level of the active region, then proceeding through an injector/relaxation region into the next active
25 region, and so on. Thus, each charge carrier that is introduced into the relevant portion of the quantum cascade laser ideally undergoes a multiplicity of (laser) transitions (corresponding to the number of repeat units), each such (laser) transition resulting in an emission of a photon of a certain wavelength, which is typically in the infrared range (e.g. 3-13 μm).

A known quantum cascade laser device is shown in Fig. 1. A mesa is provided on a first doped silicon layer, which is used for contacting a first side of the quantum cascade laser device via a bottom electrode. The mesa comprises a quantum cascade laser stack of, for example, alternating Si/SiGe or Ge/SiGe layers, on which a top electrode layer is provided for contacting a second side of the quantum cascade laser device. As is shown in Fig. 1, radiation is emitted in a direction perpendicular to a side surface of the mesa and parallel to a top surface of the silicon substrate.

The radiation emitted by these types of quantum cascade lasers is in the range of the chemical fingerprints of a lot of chemical and biological substances. For example, the quantum cascade lasers may be employed advantageously as radiation sources for absorption spectroscopy of gases and pollutants. However, there is a need for an increased output power of the quantum cascade laser in applications with a large sensing range, for example for remote sensing of gases and vapors, such as environmental (pollution) detection and security applications (e.g. anthrax detection). Such a quantum cascade laser, which has an increased output power, can also beneficially be applied in other applications such as those that include cruise control in conditions of poor visibility, collision-avoidance radar, industrial-process control and medical diagnostics such as breath analyzers. Because the power density of the side emitting quantum cascade laser device is proportional to the perimeter of the mesa, as seen in projection on the silicon substrate, the power of this device can be increased at the cost of a more than proportional increase of substrate area. A proportional increase of substrate area is achieved by a quantum cascade laser device that emits the laser beam perpendicular to the substrate.

US 6,560,259 discloses a high-power, quantum cascade laser device, including a method for fabricating it, that emits the laser beam perpendicular to the substrate surface.

This quantum cascade laser is a modified unipolar quantum cascade laser structure that incorporates grating-coupled, surface-emitting, and unstable resonance cavities. The interaction of wave beams, traveling parallel to the surface of the substrate, with a grating structure produces first and second order Bragg diffraction. The first order Bragg diffraction couples the laser light into the substrate surface normal direction for surface-emitted laser output. A disadvantage of this quantum cascade laser is that the grating structure and the mirror action of the Bragg diffraction causes energy losses thereby decreasing the power efficiency of the quantum cascade laser.

It is therefore an object of the invention to provide a quantum cascade laser device, with an improved power efficiency. The invention is defined by the independent claims. Advantageous embodiments are defined by the dependent claims.

The quantum cascade laser device according to the invention is provided in a semiconductor substrate, which has a top surface, and comprises a stack of semiconductor quantum cascade laser layers with a side surface that exposes a side of each semiconductor quantum cascade layer. The laser device emits a light beam in a direction substantially perpendicular to the side surface of the laser device, which side surface is essentially parallel to the top surface of the semiconductor substrate. The light beam inside the laser device is not reflected into another direction before it is emitted from the laser device in a direction substantially perpendicular to the top surface of the semiconductor substrate. Thus, the power loss of the laser device is reduced considerably, thereby improving the power efficiency of the device.

In an embodiment of the device according to the invention the stack of semiconductor quantum cascade laser layers is provided in a trench in the semiconductor substrate, wherein the side surface of the stack of semiconductor quantum cascade laser layers is provided along the perimeter of the trench. This embodiment advantageously employs the trench, which is a well-known and simple feature in semiconductor devices, to provide for a laser device in which the light beam is emitted in a direction substantially perpendicular to the top surface of the semiconductor substrate.

In another embodiment of the device according to the invention the stack of semiconductor quantum cascade laser layers is provided in between a first semiconductor contact layer and a second semiconductor contact layer. The first and second semiconductor contact layers confine the stack of semiconductor quantum cascade laser layers, which is the region where the laser action is initiated.

In an embodiment of the device according to the invention a top electrode layer extends over the stack of semiconductor quantum cascade laser layers. The top electrode layer provides for an electrical contact to the stack of semiconductor quantum cascade laser layers. Preferably the laser device is electrically contacted at the top surface of the substrate on a first side via the semiconductor substrate and on a second side, opposite to the first side, via the top electrode layer. The electrical contacts at the top surface of the semiconductor substrate provide for a relatively simple electrical connection that is compatible with electrical connections to other devices on the substrate.

A method of manufacturing a quantum cascade laser device according to the invention comprises the steps of:

- providing a trench in a semiconductor substrate;
- providing a stack of semiconductor quantum cascade laser layers on exposed surfaces of the trench and of the semiconductor substrate;
- depositing a top electrode layer on the stack of semiconductor quantum cascade laser layers, thereby filling the remainder of the trench; and
- removing portions of the top electrode layer and of the stack of semiconductor quantum cascade laser layers, thereby exposing a side surface of the stack of semiconductor quantum cascade laser layers.

This is a less expensive and relatively simple manufacturing method that provides the quantum cascade laser device according to the invention, which emits a light beam in a direction that is substantially perpendicular to the side surface of the laser device, which side surface is essentially parallel to the top surface of the semiconductor substrate.

Because there is no mirror action in the laser device according to the invention, this method does not require any grating or other layer structure to enable this mirror action, which makes the method according to the invention less expensive and relatively simple.

In another embodiment of the method according to the invention, the method further comprises the steps of providing electrical contacts to the substrate and the top electrode layer. In this way the electrical contact is advantageously provided on the top surface of the substrate, which is compatible with standard semiconductor processing.

In another embodiment of the method according to the invention, the step of providing a stack of semiconductor quantum cascade laser layers comprises an epitaxial growth step that provides for, in that order, a first semiconductor contact layer, the stack of semiconductor quantum cascade laser layers and a second semiconductor contact layer. In this way the stack of semiconductor quantum cascade laser layers is provided in the trench in a conformal way and with one process step the first and second semiconductor contact layers and the stack of semiconductor quantum cascade laser layers are formed, which is the region where the laser action is initiated. Preferably the first and the semiconductor contact layers comprise silicon, and the top electrode layer comprises polysilicon.

These and other aspects of the invention will be further elucidated and described with reference to the drawings, in which:

Fig. 1 is a diagrammatic cross-sectional view of an embodiment of a quantum cascade laser device according to the prior art;

Fig. 2 is a diagrammatic cross-sectional view of an embodiment of a quantum cascade laser device according to the invention;

5 Fig. 3 is a schematic top view of an embodiment of a quantum cascade laser device according to the invention; and

Figs. 4-9 are diagrammatic cross-sectional views of an embodiment of a method of manufacturing a quantum cascade laser device according to the invention.

10

The Figures are not drawn to scale. In general, identical components are denoted by the same reference numerals in the Figures.

Fig. 1 shows a diagrammatic cross-sectional view of a known quantum cascade laser device 10. A first doped silicon layer 2, which is used for contacting a first side
15 of the quantum cascade laser via a bottom electrode 3, is provided on a silicon substrate 1, and on the first doped silicon layer 2 a mesa 7 is provided. The mesa 7 comprises a quantum cascade laser stack 4 of, for example, alternating Si/SiGe or Ge/SiGe layers, on which a second doped silicon layer 5 and a top electrode layer 6 are provided. As shown, radiation L is emitted in a direction perpendicular to the side surface of the mesa 7 and parallel to the top
20 surface of the silicon substrate 1. The power density of the quantum cascade laser device 10 can be increased by a proportional increase of the perimeter of the mesa 7 as seen in projection on the silicon substrate 1. Thus an increase of the power of the quantum cascade laser device 10 costs a more than proportional increase of substrate area.

Increasing the power at the cost of a smaller increase of the substrate area, in
25 this case a proportional increase, is achieved in the case that the quantum cascade laser emits the laser beam perpendicular to the substrate. Fig. 2 shows a diagrammatic cross-sectional view of an embodiment of a quantum cascade laser device 100 according to the invention. A trench is provided in a, in this case, silicon substrate 11. The trench is filled with, in that order, a first doped silicon layer 12, a stack of quantum cascade laser layers 14, a second
30 doped silicon layer 15, and a polysilicon layer 16. The first doped silicon layer 12 is electrically connected to a first contact 17 via the silicon substrate 11, and the second doped silicon layer 15 is electrically connected to a second contact 18, via the polysilicon layer 16. By applying a voltage between the first contact 17 and the second contact 18, an electrical field is created over the stack of quantum cascade laser layers 14, which initiates the laser

action and generates a laser beam L that is emitted in a direction perpendicular to the side surface 13 of the stack of quantum cascade layers 14 and hence also perpendicular to the top surface of the silicon substrate 11.

Fig. 3 shows a schematic top view of an embodiment of a quantum cascade laser device 101. A 3x3 array of the quantum cascade laser device 101 is shown in the silicon substrate 11, wherein each quantum cascade laser device 101 is shaped as a square. The square shape is not essential, for example a rectangular shape is also possible. A top surface of the polysilicon layer 16 is surrounded by the second doped silicon layer 15, which is surrounded by the side surface 13 of the stack of quantum cascade laser layers 14, which is surrounded by a side region of the first doped silicon layer 12. Increasing the area of the square occupied by the quantum cascade laser device 101 proportionally increases the power density of the quantum cascade laser device 101.

Figs. 4 to 9 illustrate cross-sectional views of an embodiment of a method of manufacturing a quantum cascade laser device 100 according to the invention. As is shown in Fig. 4, a hard mask layer 21 of, for example, silicon oxide is deposited on the silicon substrate 11.

Then, as is shown in Fig. 5, a window 22 is formed in the hard mask layer 21 by using standard lithographic and etching techniques.

Subsequently, as is shown in Fig. 6, a trench 23 is formed in the silicon substrate 11 using a standard etching technique in which the hard mask layer 21 defines the region where the trench 23 is formed.

Then, an epitaxial growth step forms, in that order, a first doped silicon layer 12, a stack of quantum cascade laser layers 14 and a second doped silicon layer 15, as is shown in Fig. 7. A further trench 24 remains, because the trench 23 is not filled entirely. Note that the portion of the layers that extends over the hard mask layer 21 will be polycrystalline, and the portion of the layers that are formed inside the trench 23 on the silicon substrate 11 will be monocrystalline. The stack of quantum cascade laser layers 14 comprises, for example, alternating silicon and silicon germanium layers in which parameters such as, for example, the thickness of each layer and the germanium content may be varied to obtain an optimum quantum cascade laser device.

Thereafter, a polysilicon layer 16 is deposited which fills the further trench 24, as is shown in Fig. 8.

Then a planarization step is applied, for example a chemical mechanical polishing technique, which planarizes the surface of the quantum cascade laser device 100

and exposes a side surface 13 of the stack of quantum cascade laser layers 14, as is shown in Fig. 9.

Then an isolation layer 20, a first contact 17 and a second contact 18 are formed using standard techniques, resulting in the stack of quantum cascade laser device 100 as is shown in Fig. 2.

In summary, the invention provides a quantum cascade laser device in a semiconductor substrate, which quantum cascade laser device comprises a plurality of semiconductor layers having a side surface that exposes a side of each semiconductor layer. The quantum cascade laser device emits a light beam in a direction substantially perpendicular to the side surface of the quantum cascade laser device, which side surface is essentially parallel to a top surface of the semiconductor substrate. The power loss of the quantum cascade laser device is reduced considerably, because the light beam is not diffracted or reflected before it is emitted from the quantum cascade laser device, which improves the power efficiency of the quantum cascade laser device. The invention further provides a method of manufacturing such a quantum cascade laser device.

It should be noted that the above-mentioned embodiments illustrate rather than limit the invention, and that those skilled in the art will be able to design many alternative embodiments without departing from the scope of the appended claims. In the claims, any reference signs placed between parentheses shall not be construed as limiting the claim. The word “comprising” does not exclude the presence of other elements or steps than those listed in a claim. The word “a” or “an” preceding an element does not exclude the presence of a plurality of such elements.

CLAIMS:

1. A quantum cascade laser device (100,101) in a semiconductor substrate (11), which has a top surface, the laser device (100,101) comprising a stack of semiconductor quantum cascade laser layers (14) with a side surface (13) that exposes a side of each semiconductor quantum cascade layer, the laser device (100,101) emitting a light beam (L) in a direction substantially perpendicular to the side surface (13) of the laser device (100,101), which side surface (13) is essentially parallel to the top surface of the semiconductor substrate (11).

2. A device as claimed in claim 1, in which the stack of semiconductor quantum cascade laser layers (14) is provided in a trench (23) in the semiconductor substrate (11), wherein the side surface (13) of the stack of semiconductor quantum cascade laser layers (14) is provided along the perimeter of the trench (23).

3. A device as claimed in claim 1, in which the stack of semiconductor quantum cascade laser layers (14) is provided in between a first semiconductor contact layer (12) and a second semiconductor contact layer (15).

4. A device as claimed in claim 1, in which a top electrode layer (16) extends over the stack of semiconductor quantum cascade laser layers (14).

5. A device as claimed in claim 4, in which the laser device (100,101) is electrically contacted at the top surface of the substrate (11) on a first side via the semiconductor substrate (11) and on a second side, opposite to the first side, via the top electrode layer (16).

6. A method of manufacturing a quantum cascade laser device (100,101), the method comprising the steps of:

- providing a trench (23) in a semiconductor substrate (11); and

- providing a stack of semiconductor quantum cascade laser layers (14) on exposed side surfaces of the trench (23).

7. A method as claimed in claim 6, the method further comprising the steps of:

5 - depositing a top electrode layer (16) on the stack of semiconductor quantum cascade laser layers (14), thereby filling the remainder of the trench (23); and

- removing portions of the top electrode layer (16) and of the stack of semiconductor quantum cascade laser layers (14), thereby exposing a side surface (13) of the stack of semiconductor quantum cascade laser layers (14).

10 8. A method as claimed in claim 7, the method further comprising the steps of providing electrical contacts (17,18) to the semiconductor substrate (11) and the top electrode layer (16).

15 9. A method as claimed in claim 6, wherein the step of providing a stack of semiconductor quantum cascade laser layers (14) comprises an epitaxial growth step that provides for, in that order, a first semiconductor contact layer (12), the stack of semiconductor quantum cascade laser layers (14) and a second semiconductor contact layer (15).

20 10. A method as claimed in claim 9, wherein the first and the second semiconductor contact layers (12,15) comprise silicon, and the top electrode layer (16) comprises polysilicon.

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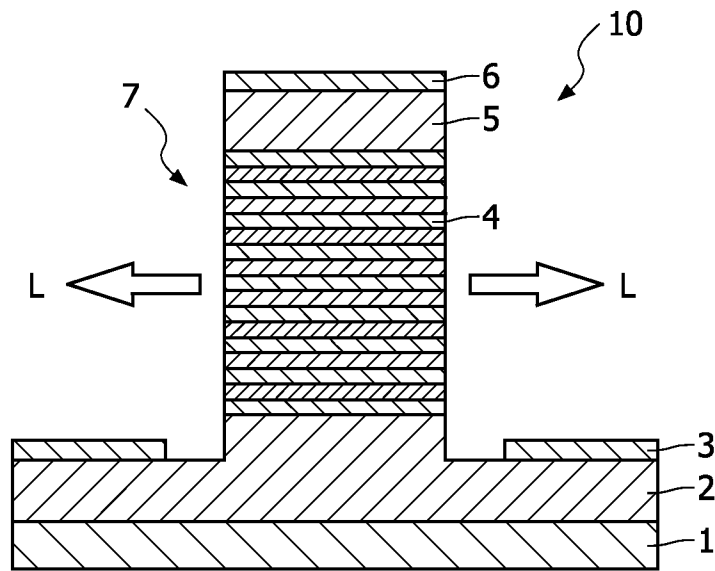


FIG. 1

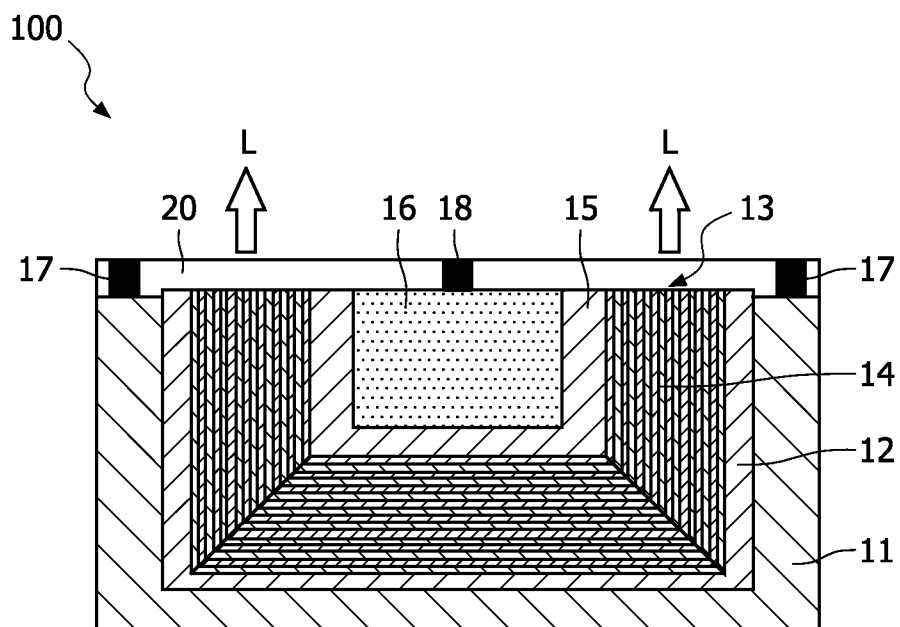


FIG. 2

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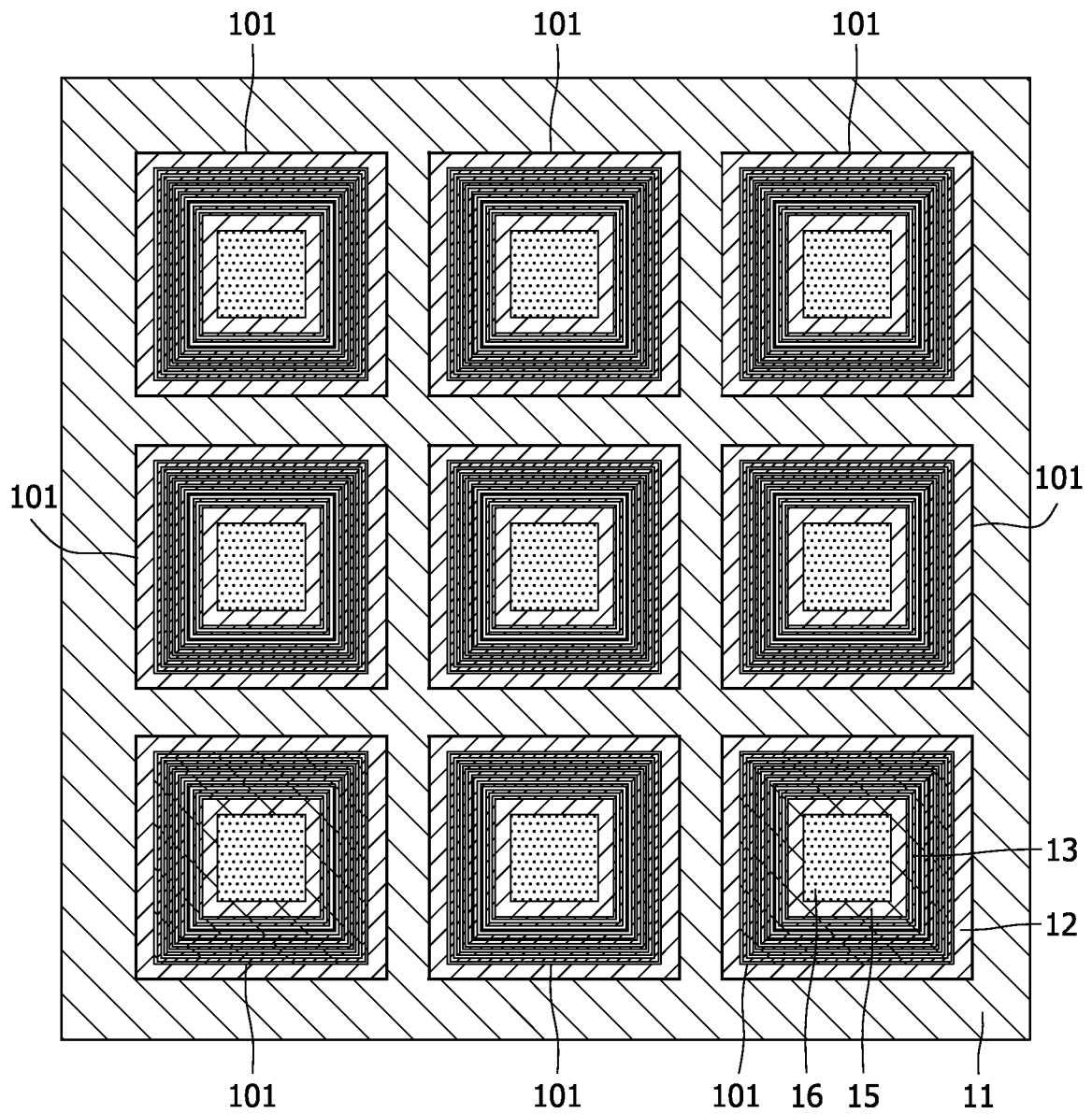


FIG. 3

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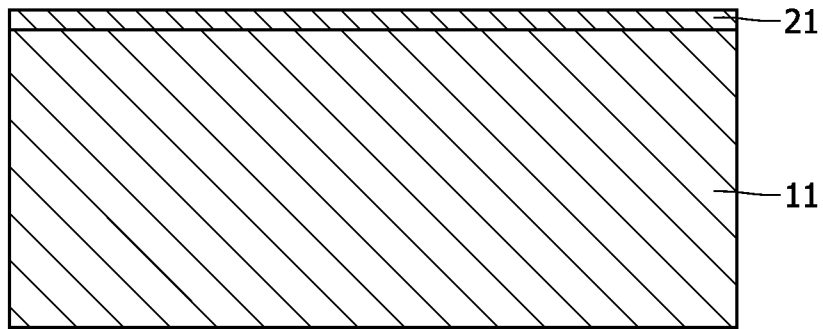


FIG. 4

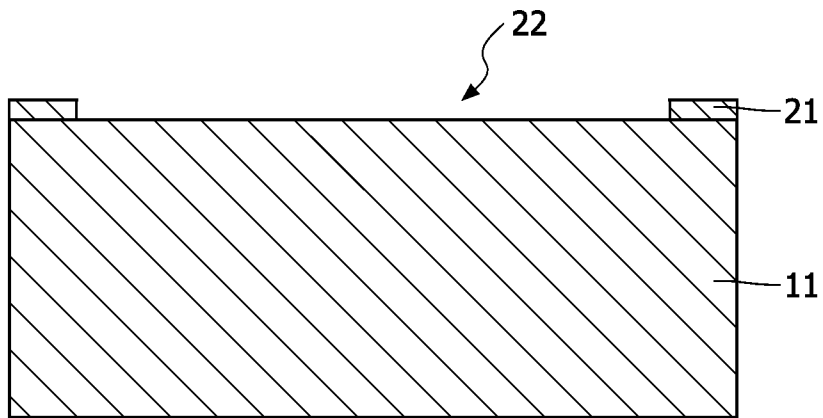


FIG. 5

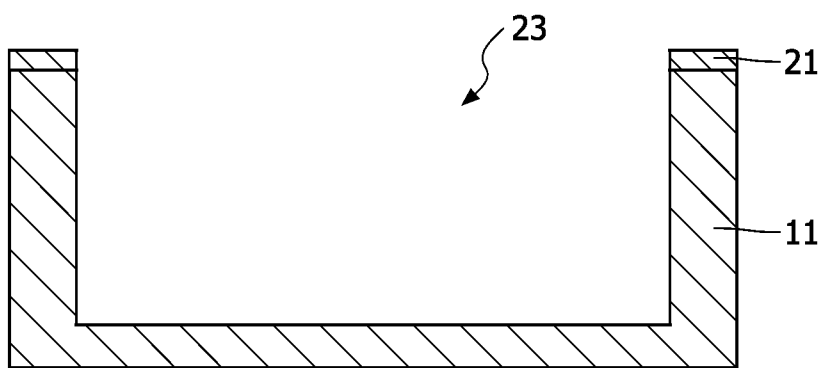


FIG. 6

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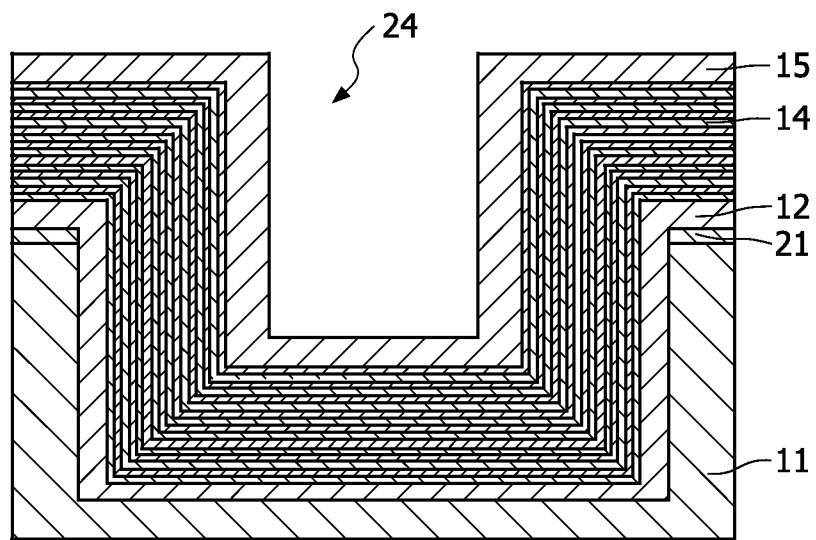


FIG. 7

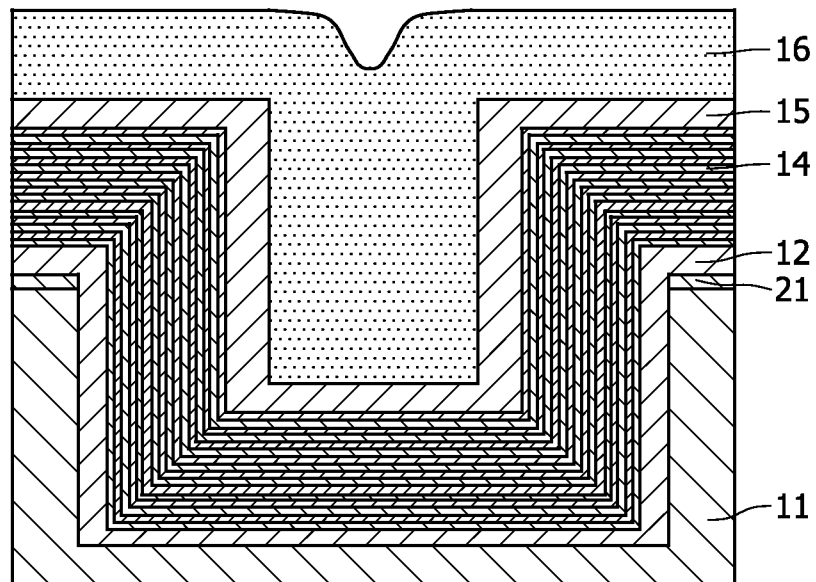


FIG. 8

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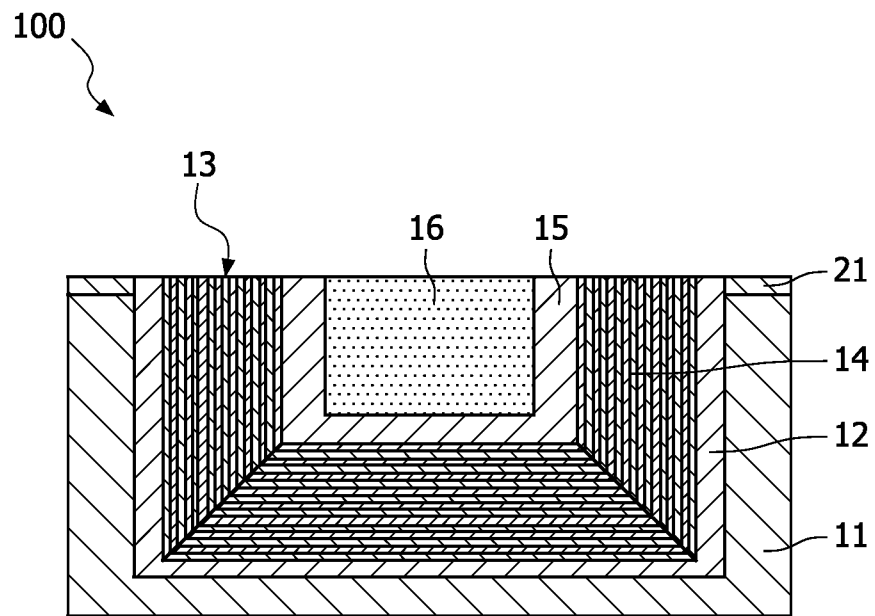


FIG. 9

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference PH005940W01	FOR FURTHER ACTION see Form PCT/ISA/220 as well as, where applicable, item 5 below.	
International application No. PCT/IB2007/051825	International filing date (<i>day/month/year</i>) 14/05/2007	(Earliest) Priority Date (<i>day/month/year</i>) 17/05/2006
Applicant NXP B.V.		

This international search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 3 sheets.

☒ It is also accompanied by a copy of each prior art document cited in this report.

1. Basis of the report

a. With regard to the **language**, the international search was carried out on the basis of:

- ☒ the international application in the language in which it was filed
☐ a translation of the international application into _____, which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b))

b. ☐ With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, see Box No. I.

2. ☐ **Certain claims were found unsearchable** (See Box No. II)

3. ☐ **Unity of invention is lacking** (see Box No. III)

4. With regard to the **title**,

- ☐ the text is approved as submitted by the applicant
☒ the text has been established by this Authority to read as follows:

QUANTUM CASCADE SURFACE EMITTING SEMICONDUCTOR LASER DEVICE AND METHOD OF MANUFACTURING A SEMICONDUCTOR LASER DEVICE

5. With regard to the **abstract**,

- ☒ the text is approved as submitted by the applicant
☐ the text has been established, according to Rule 38.2(b), by this Authority as it appears in Box No. IV. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority

6. With regard to the **drawings**,

- a. the figure of the **drawings** to be published with the abstract is Figure No. 2
☒ as suggested by the applicant
☐ as selected by this Authority, because the applicant failed to suggest a figure
☐ as selected by this Authority, because this figure better characterizes the invention
b. ☐ none of the figures is to be published with the abstract

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2007/051825

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01S5/18 H01S5/183 H01S5/34

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01S

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

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

EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 951 076 A2 (HEWLETT PACKARD CO [US] LUMILEDS LIGHTING LLC [US]) 20 October 1999 (1999-10-20) figures 4A-4E paragraphs [0030], [0038], [0040], [0048] - [0055]	1-10
X	JP 2001 308458 A (SONY CORP) 2 November 2001 (2001-11-02) abstract; figure 9	1-10
P, X	EP 1 734 625 A (AVAGO TECHNOLOGIES ECBU IP SIN [SG]) 20 December 2006 (2006-12-20) figure 4	1-10
A	US 6 560 259 B1 (HWANG WEN-YEN [US]) 6 May 2003 (2003-05-06) cited in the application the whole document	1, 6

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

- *A* document defining the general state of the art which is not considered to be of particular relevance
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- *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the international filing date but later than the priority date claimed

- *T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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- *Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- *&* document member of the same patent family

Date of the actual completion of the international search

1 October 2007

Date of mailing of the international search report

15/10/2007

Name and mailing address of the ISA/

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Authorized officer

Lendroit, Stéphane

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2007/051825

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
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