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(54) **RADIATION EMITTER**

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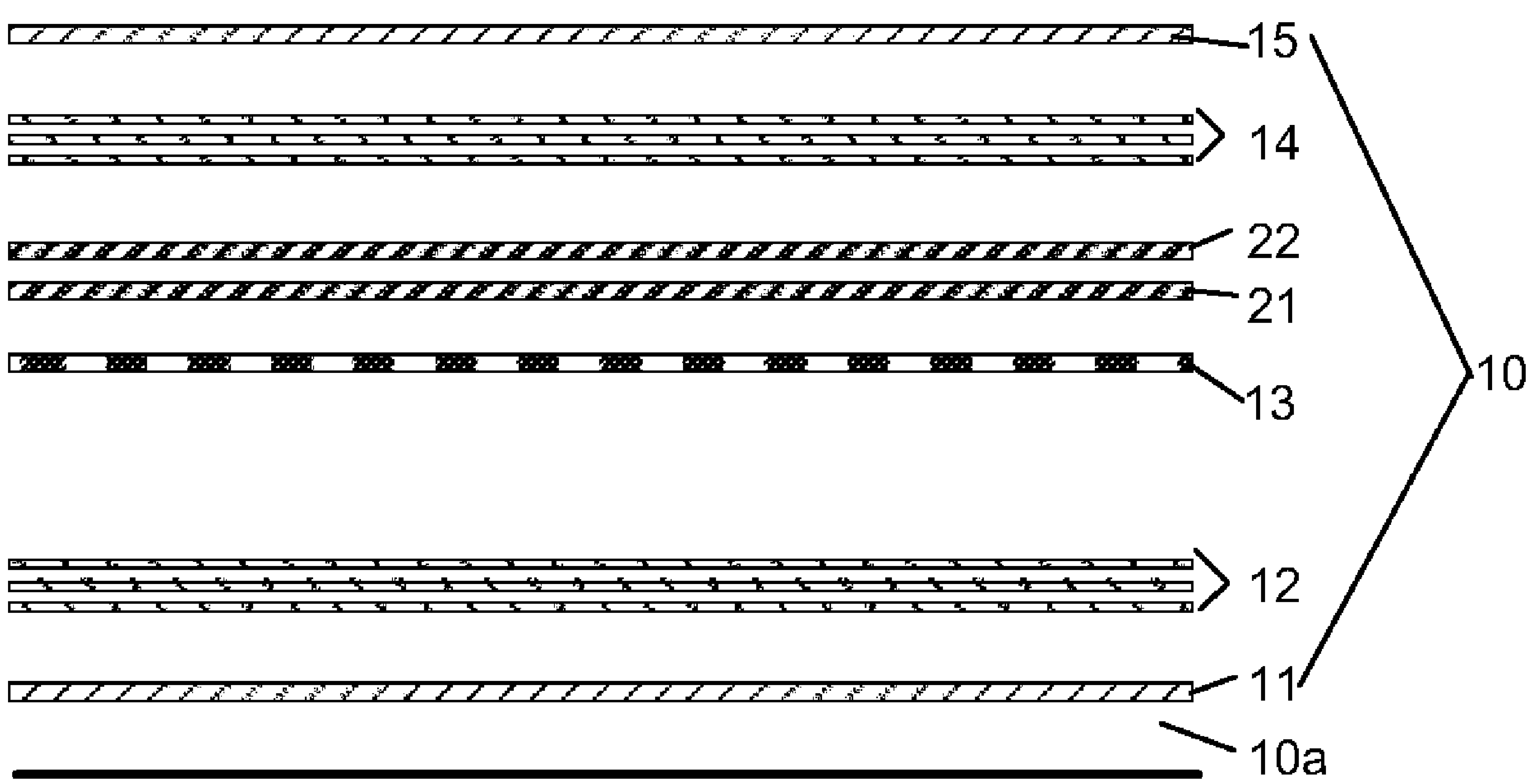
(57) **ABSTRACT**

An exemplary embodiment of the invention relates to a method of fabricating a radiation emitter (**100**) comprising the steps of fabricating a layer stack (**10**) that comprises a first reflector (**12**), an active region (**13**), an oxidizable layer (**21-24**), and a second reflector (**14**); and locally removing the layer stack (**10**), and thereby forming a mesa (M) of the radiation emitter (**100**), wherein said mesa (M) comprises the first reflector (**12**), the active region (**13**), the oxidizable layer (**21-24**) and the second reflector (**14**), wherein before or after locally removing the layer stack (**10**) and forming said mesa (M) the following steps are carried out: vertically etching blind holes (**30**) inside the layer stack (**10**), wherein the blind holes (**30**) vertically extend at least to the oxidizable layer (**21-24**) and expose the oxidizable layer (**21-24**); and oxidizing the oxidizable layer (**21-24**) via the sidewalls (**31**) of the blind holes (**30**) in lateral direction, wherein from each hole an oxidation front (**32**) radially moves outwards and wherein the etching is terminated before the entire oxidizable layer (**21-24**) is oxidized, thereby forming at least two unoxidized apertures, (**40**) each of which is limited by at least three oxidation fronts (**32**), inside the mesa.



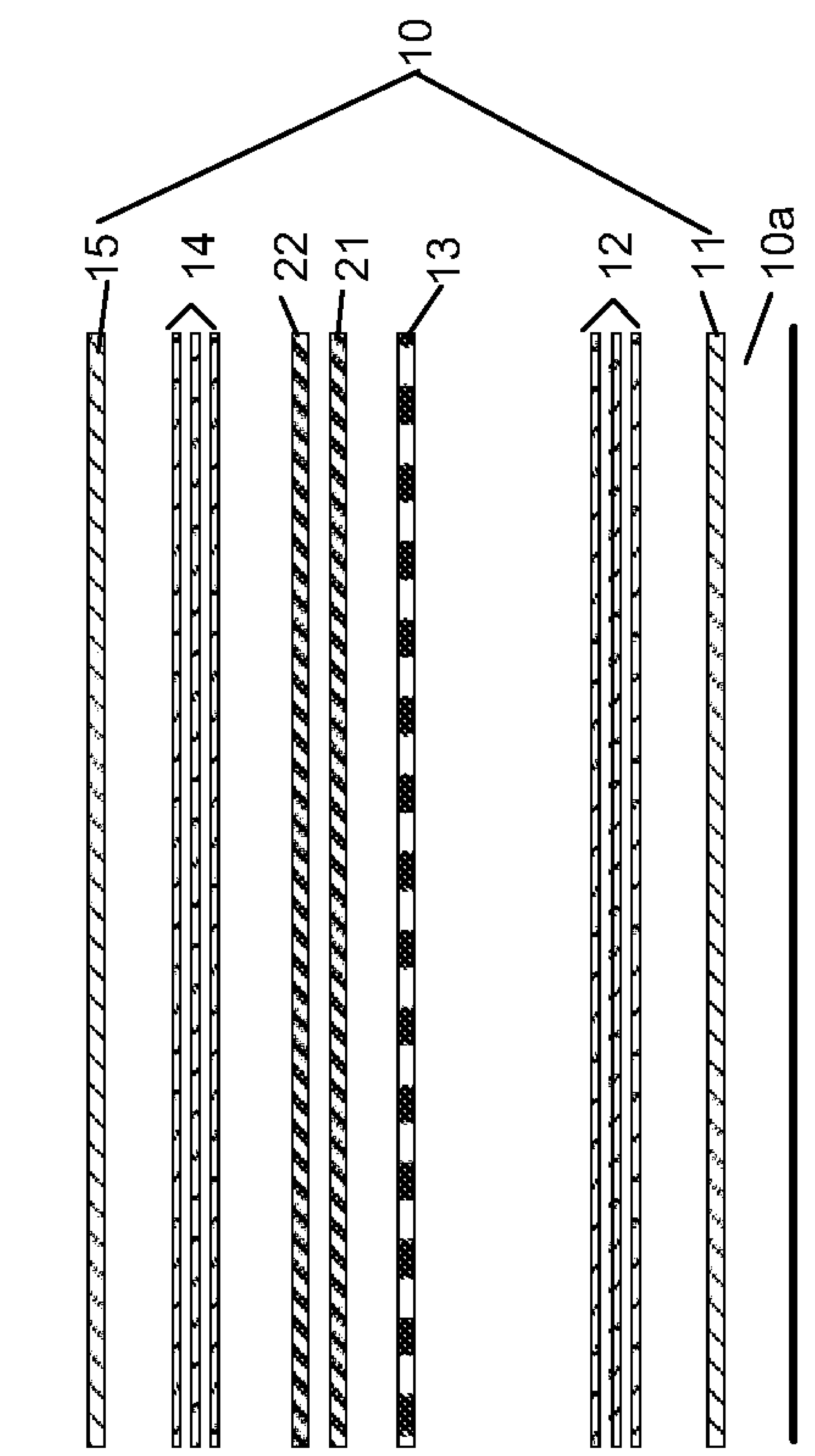


Fig. 1

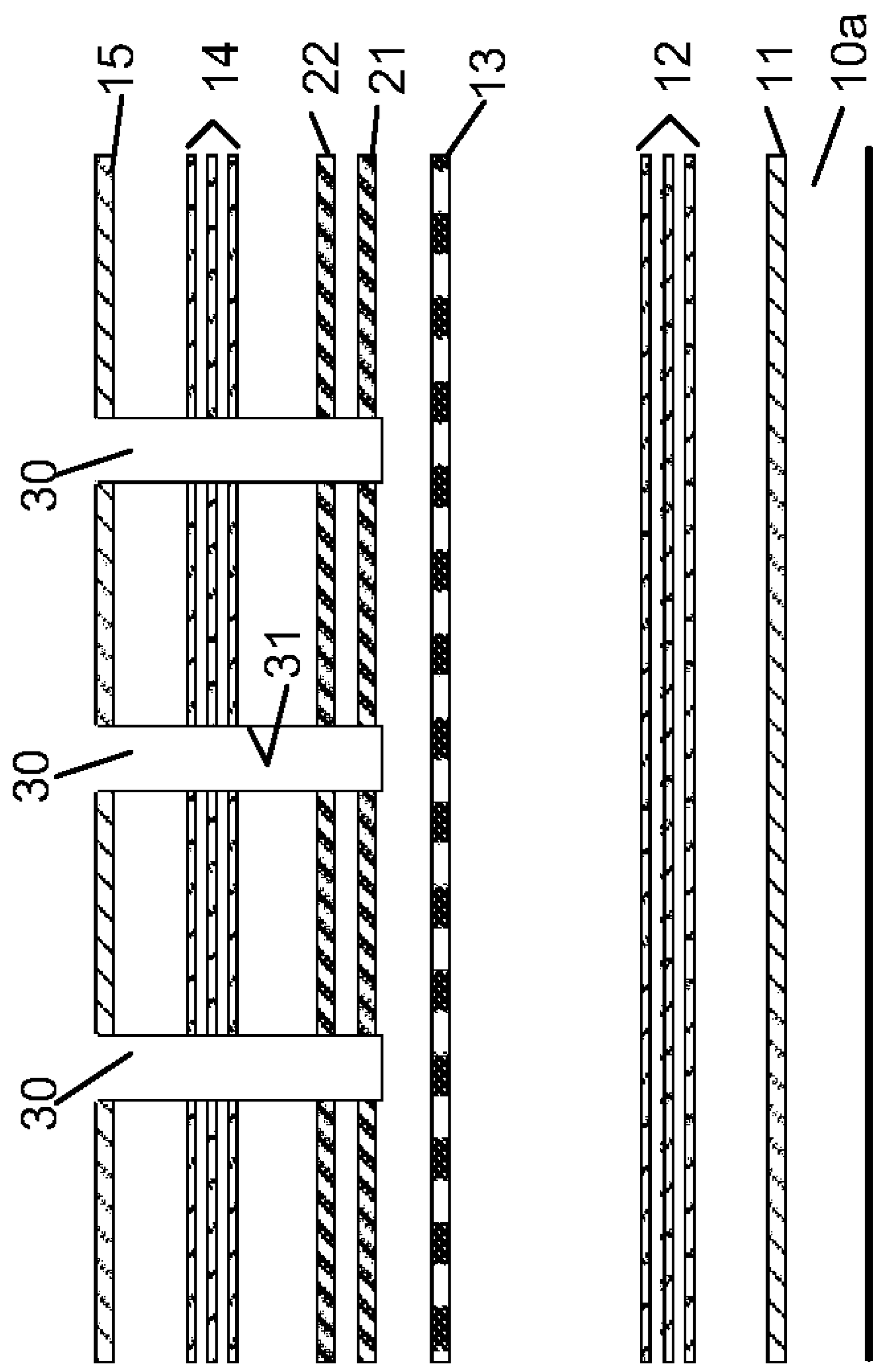


Fig. 2

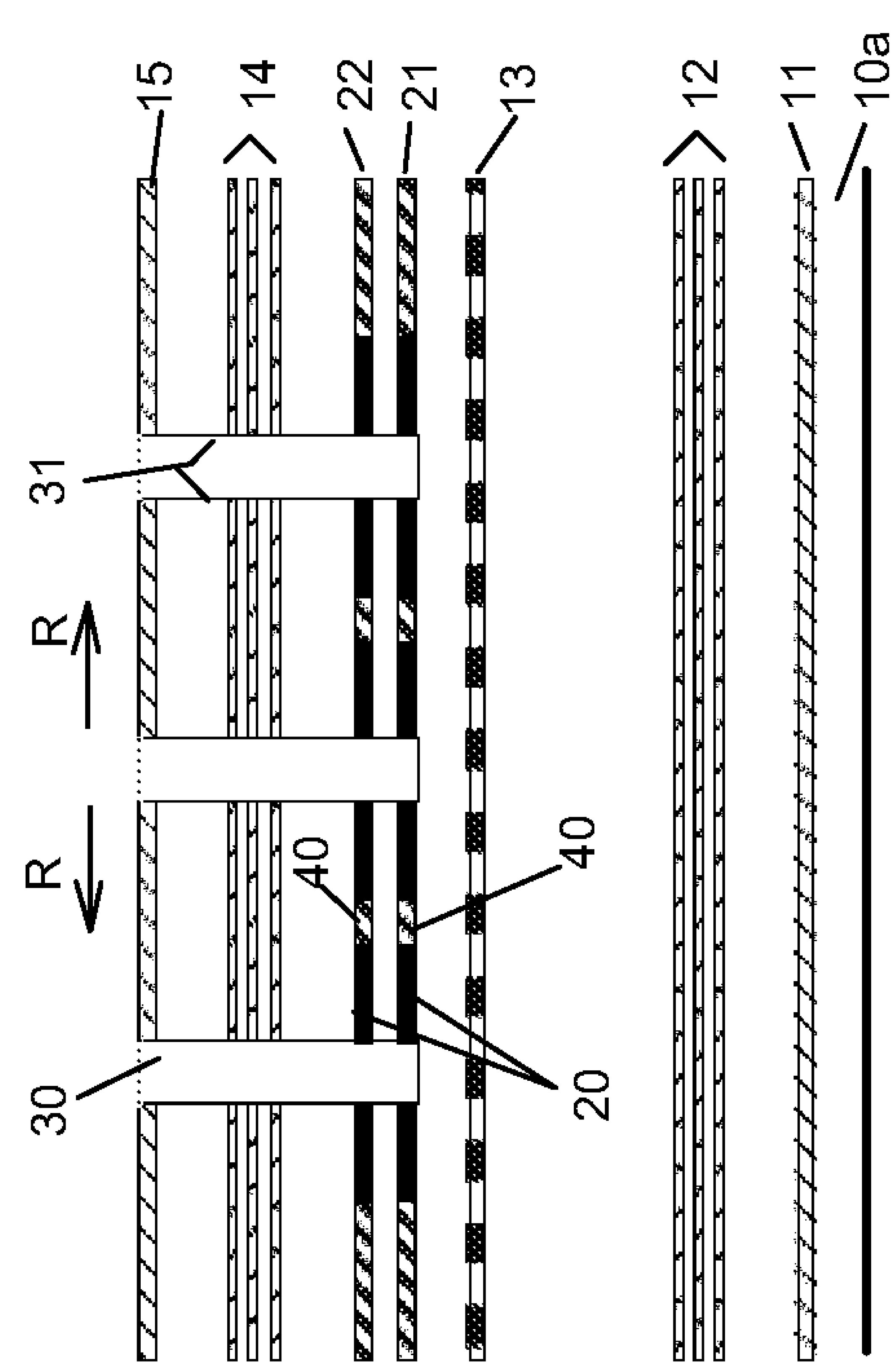


Fig. 3

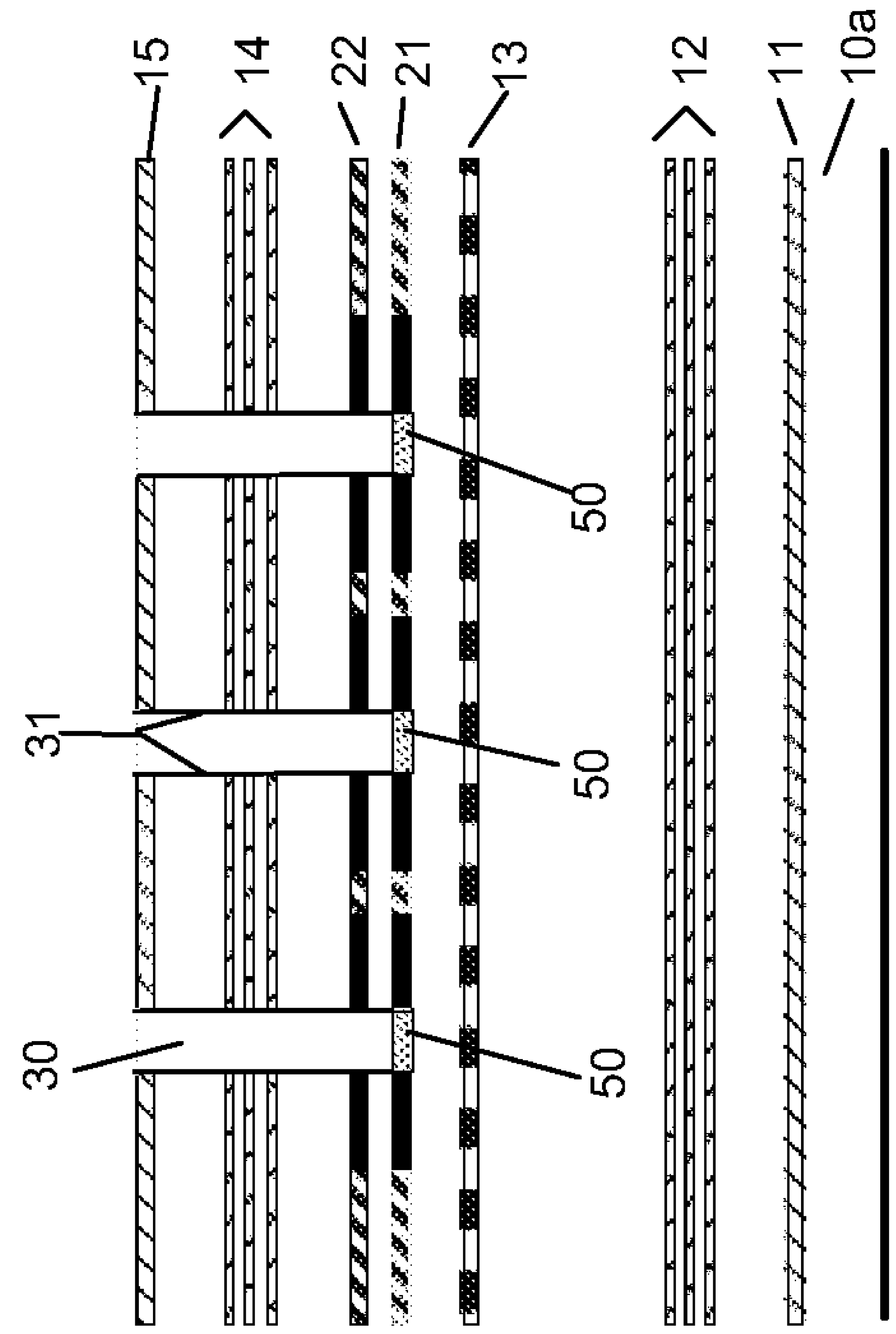


Fig. 4

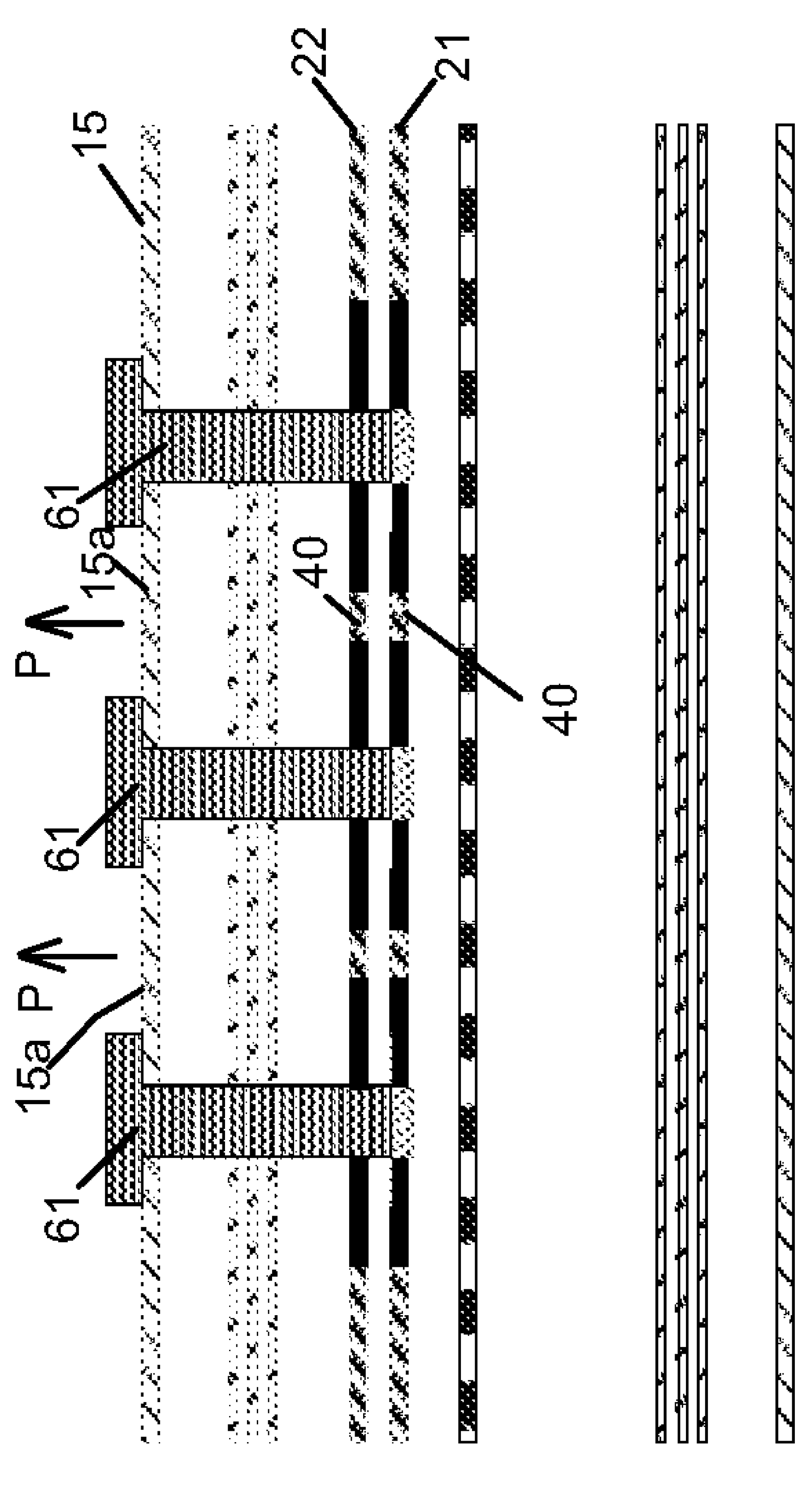


Fig. 5

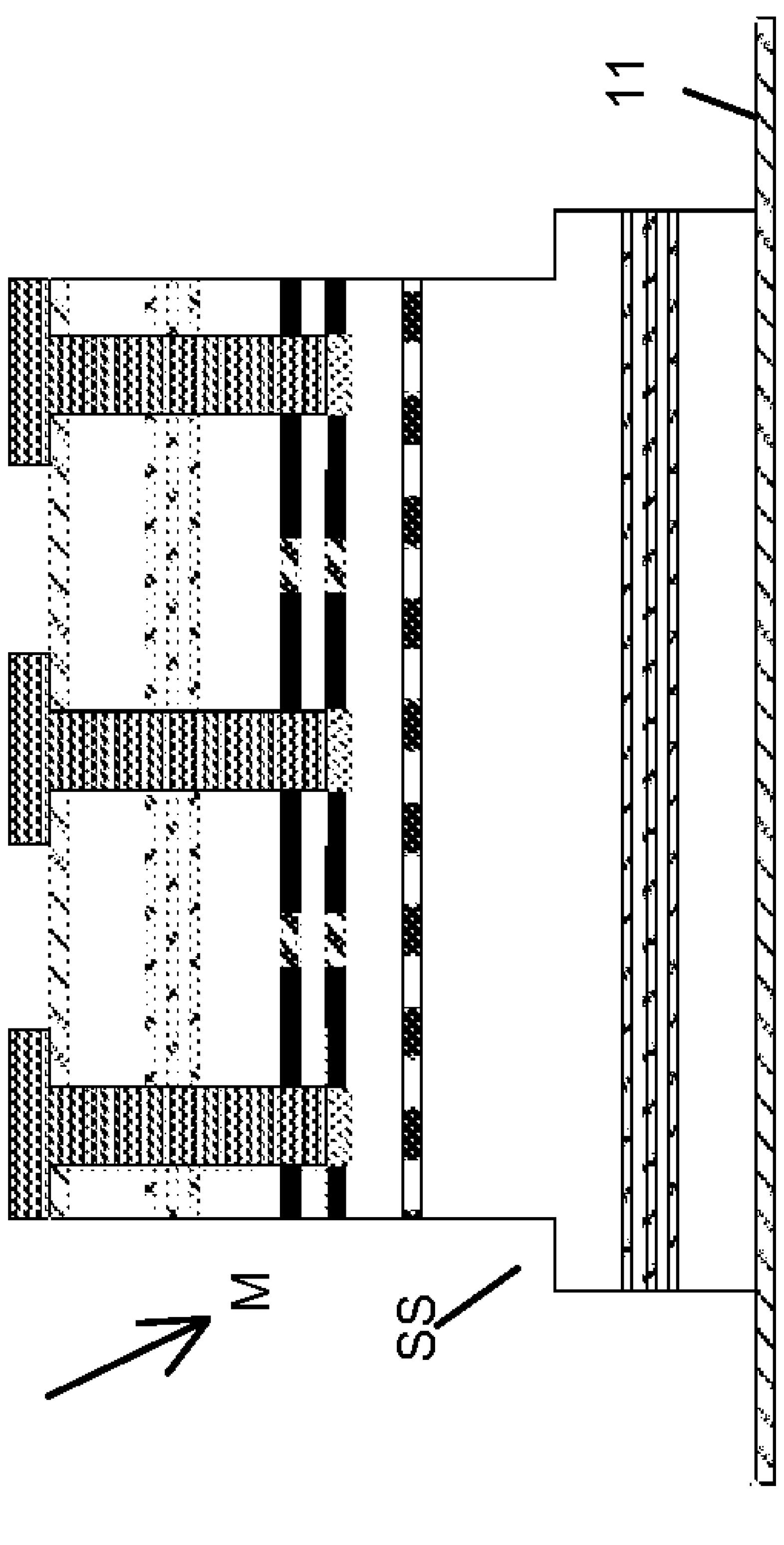


Fig. 6

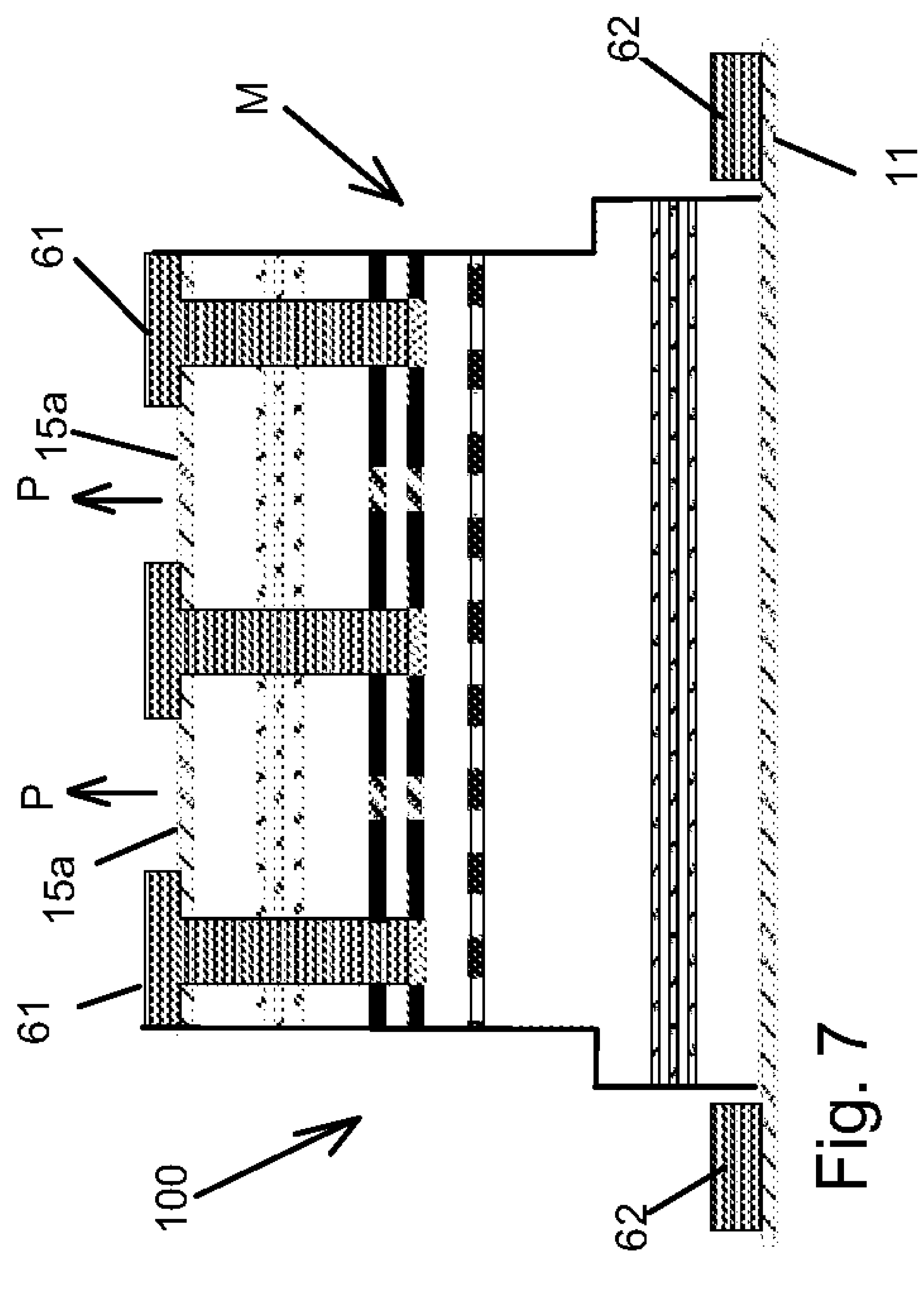


Fig. 7

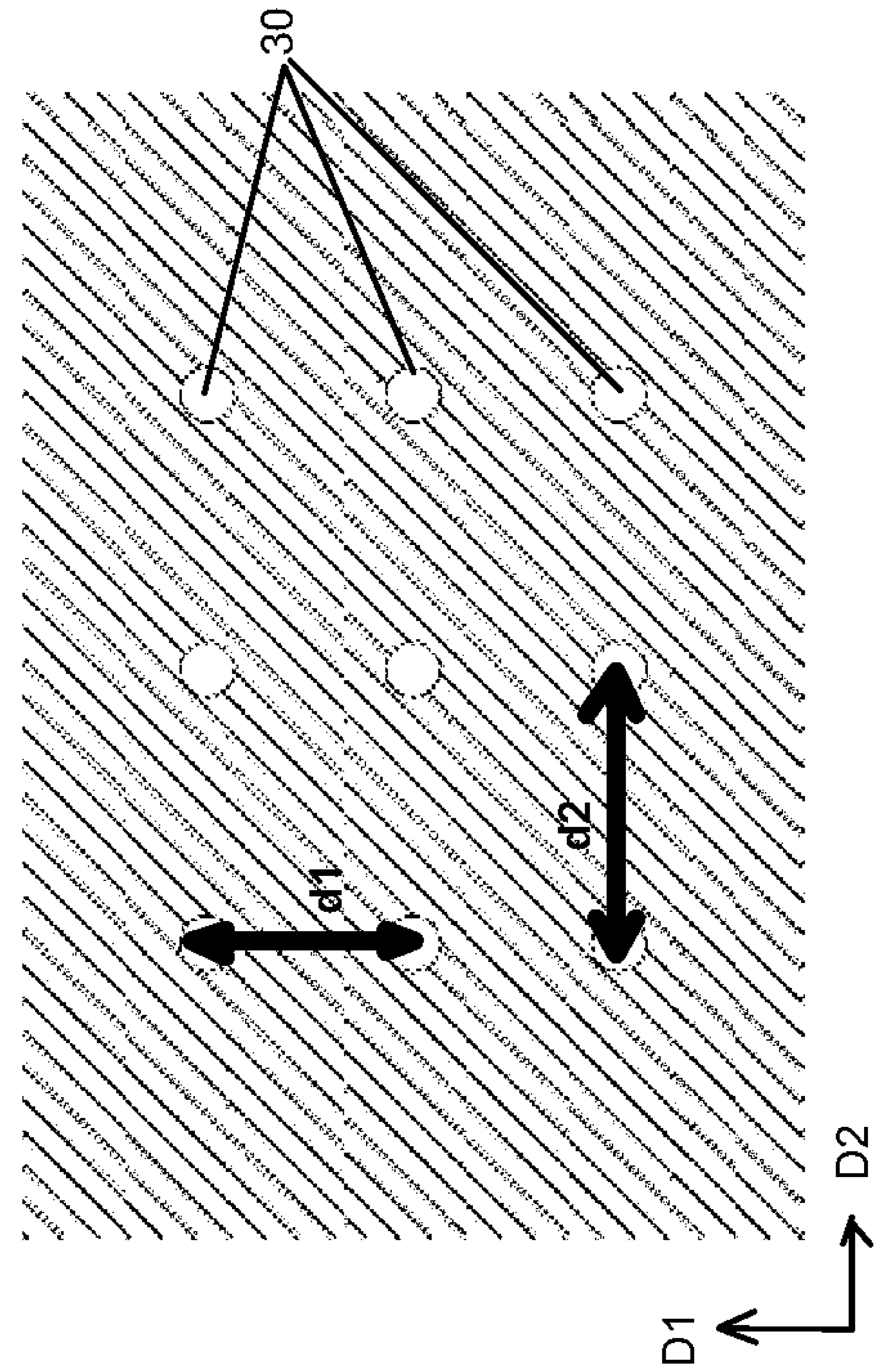


Fig. 8

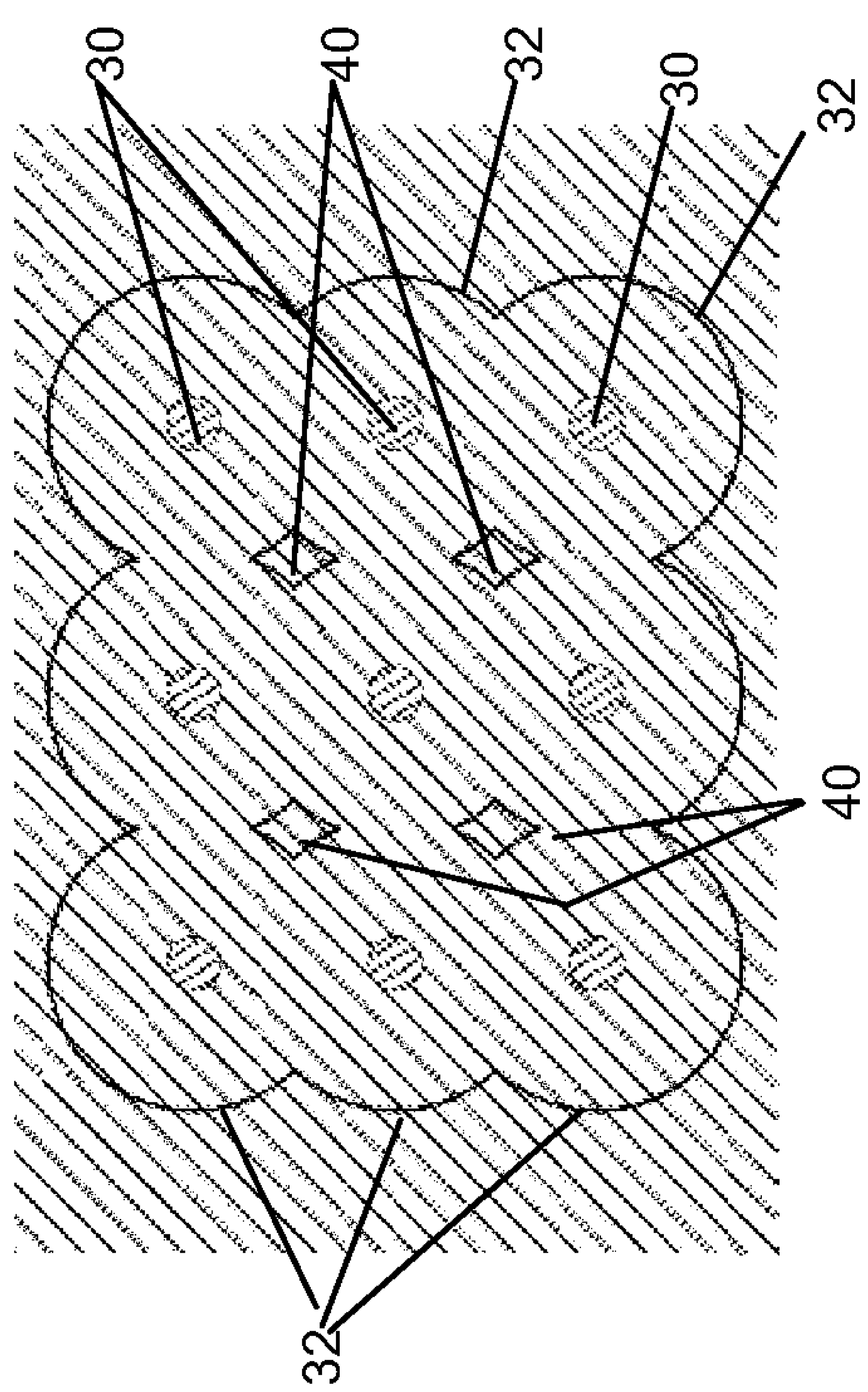


Fig. 9

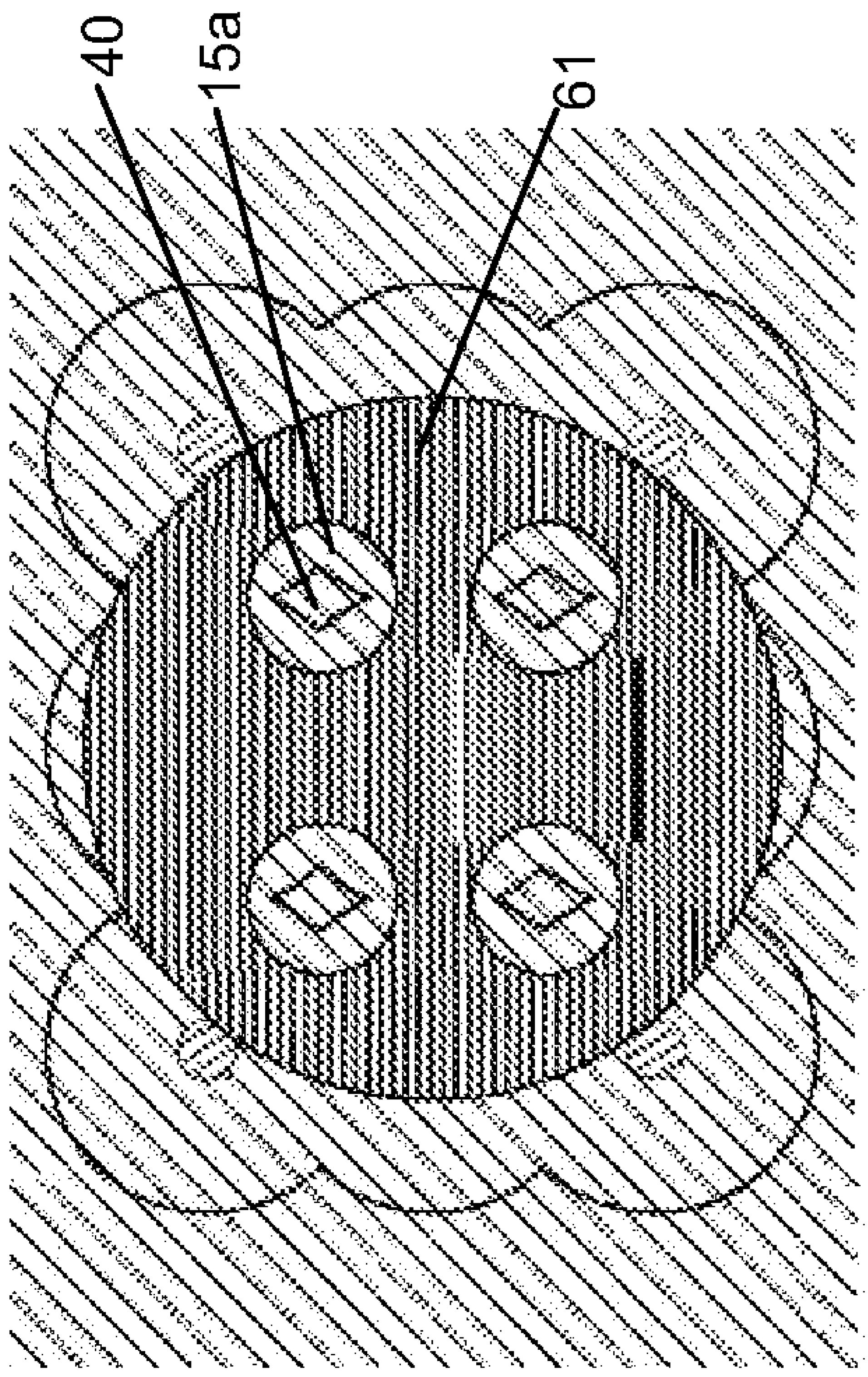


Fig. 10

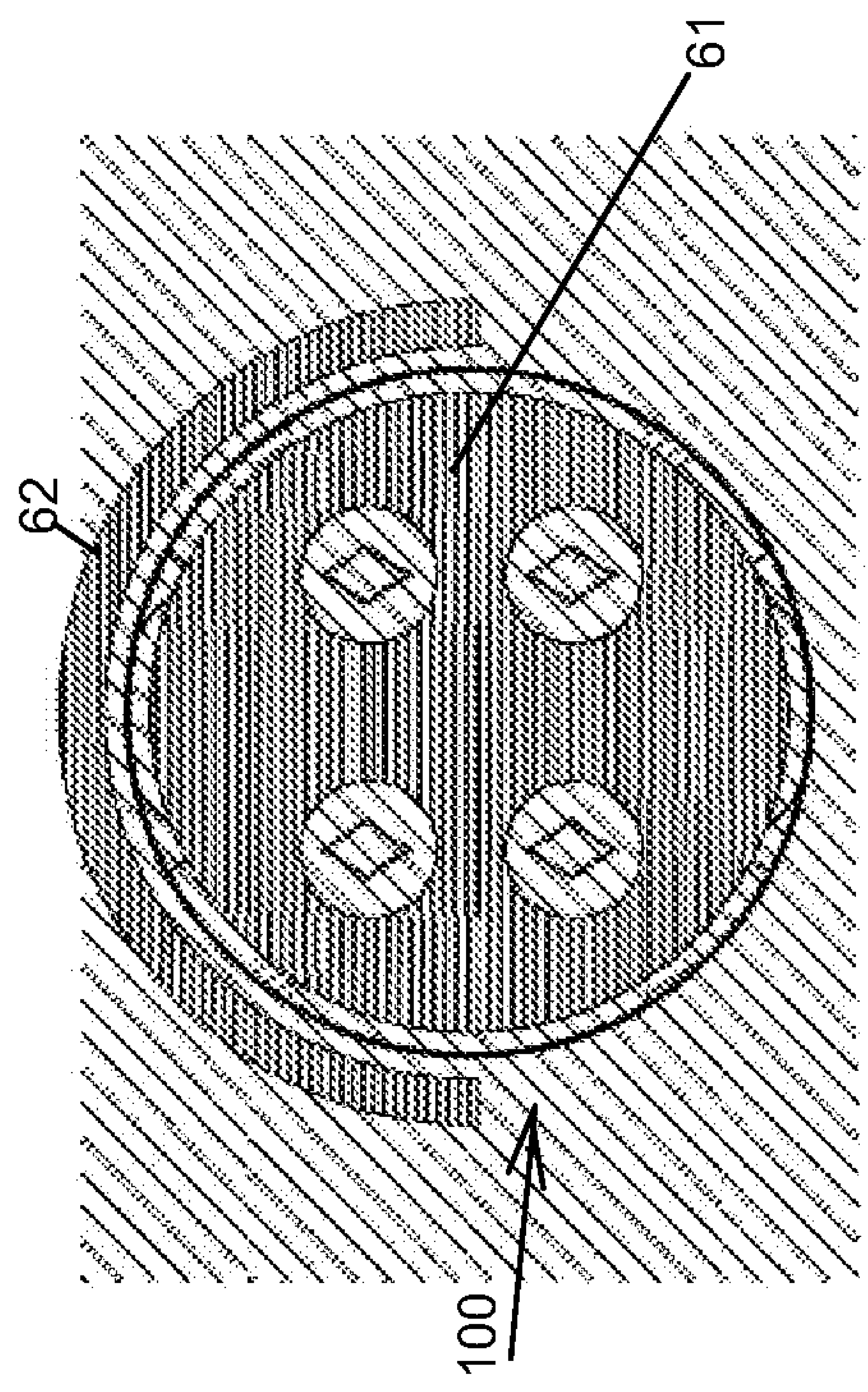


Fig. 11

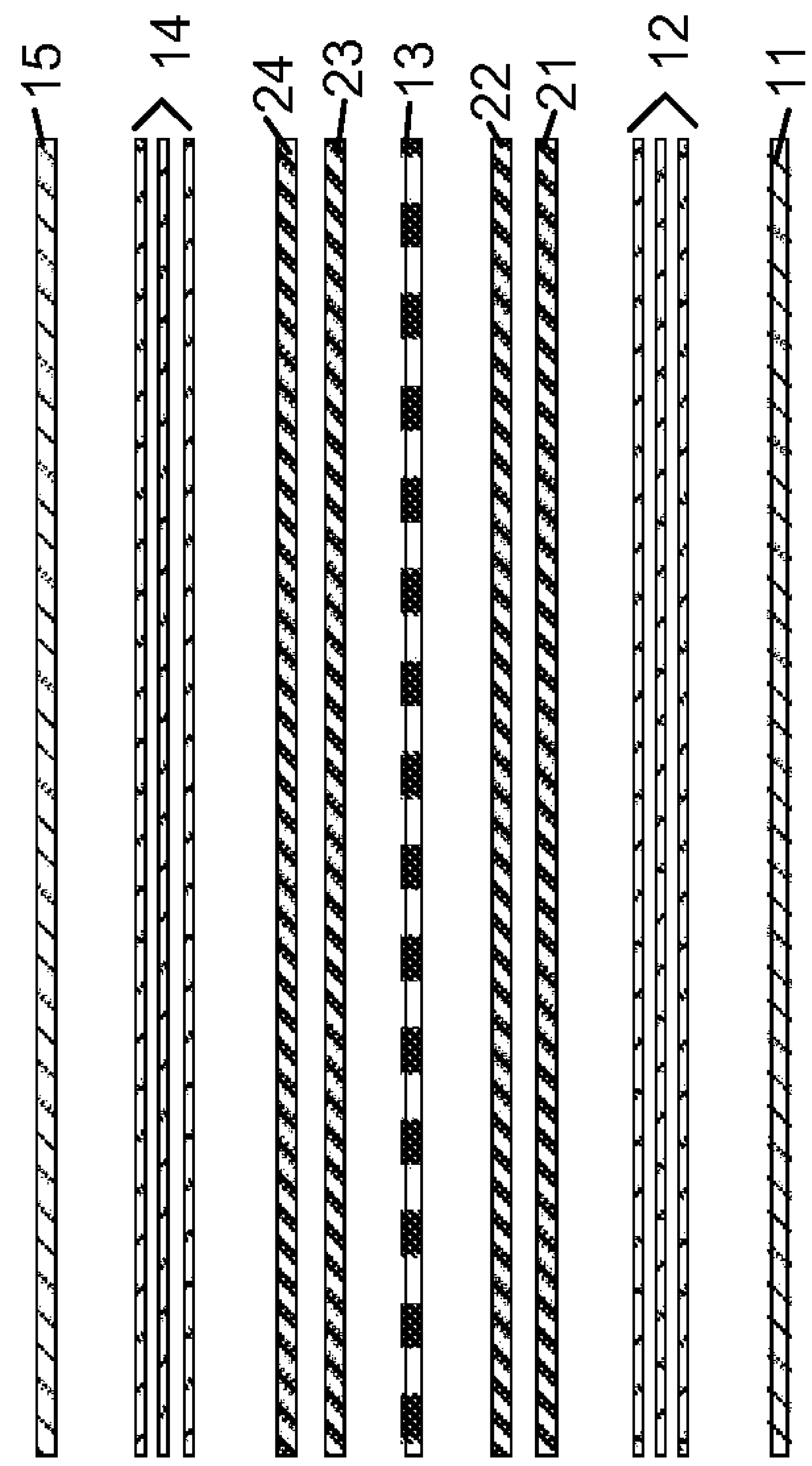


Fig. 12

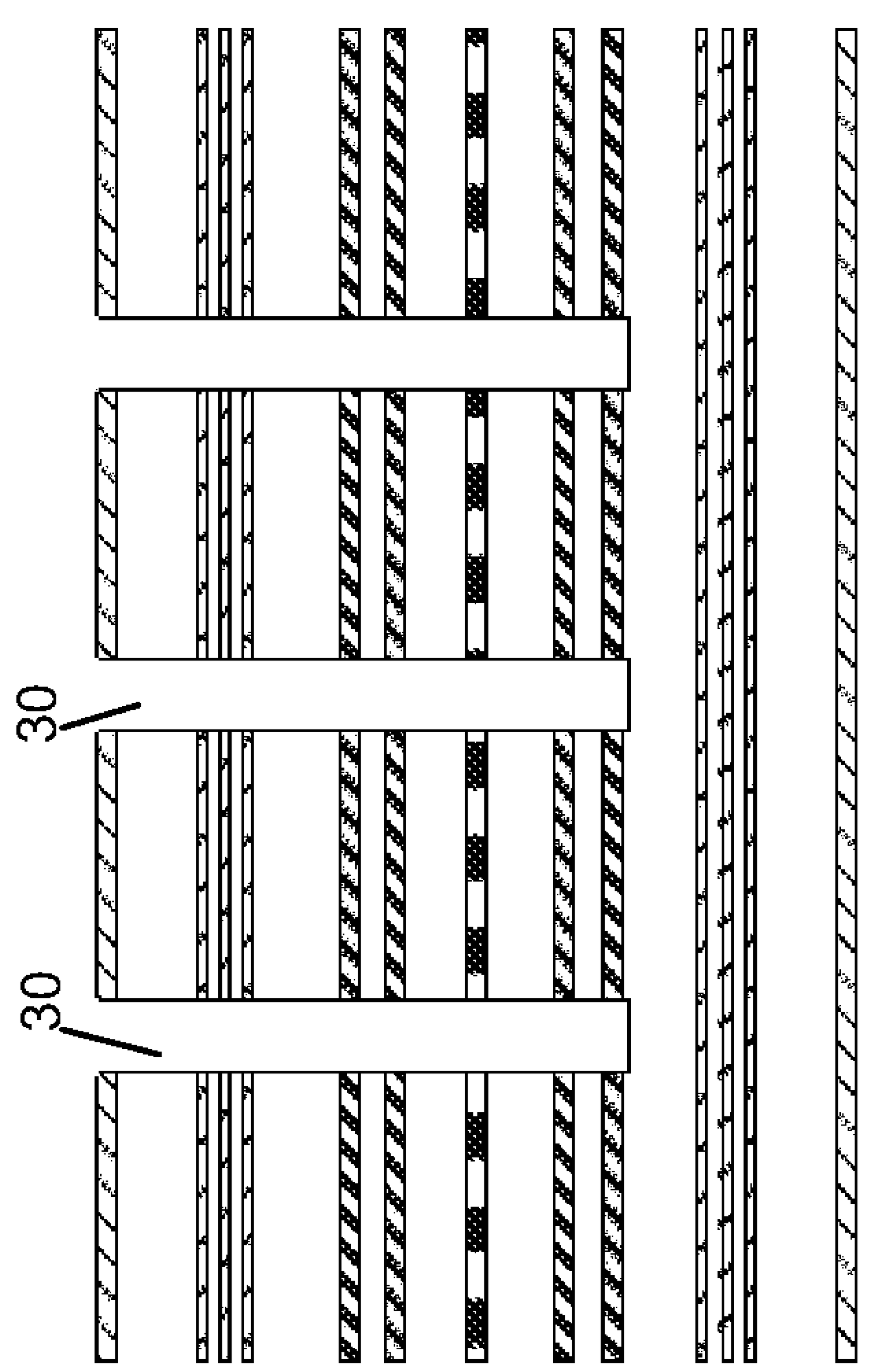


Fig. 13

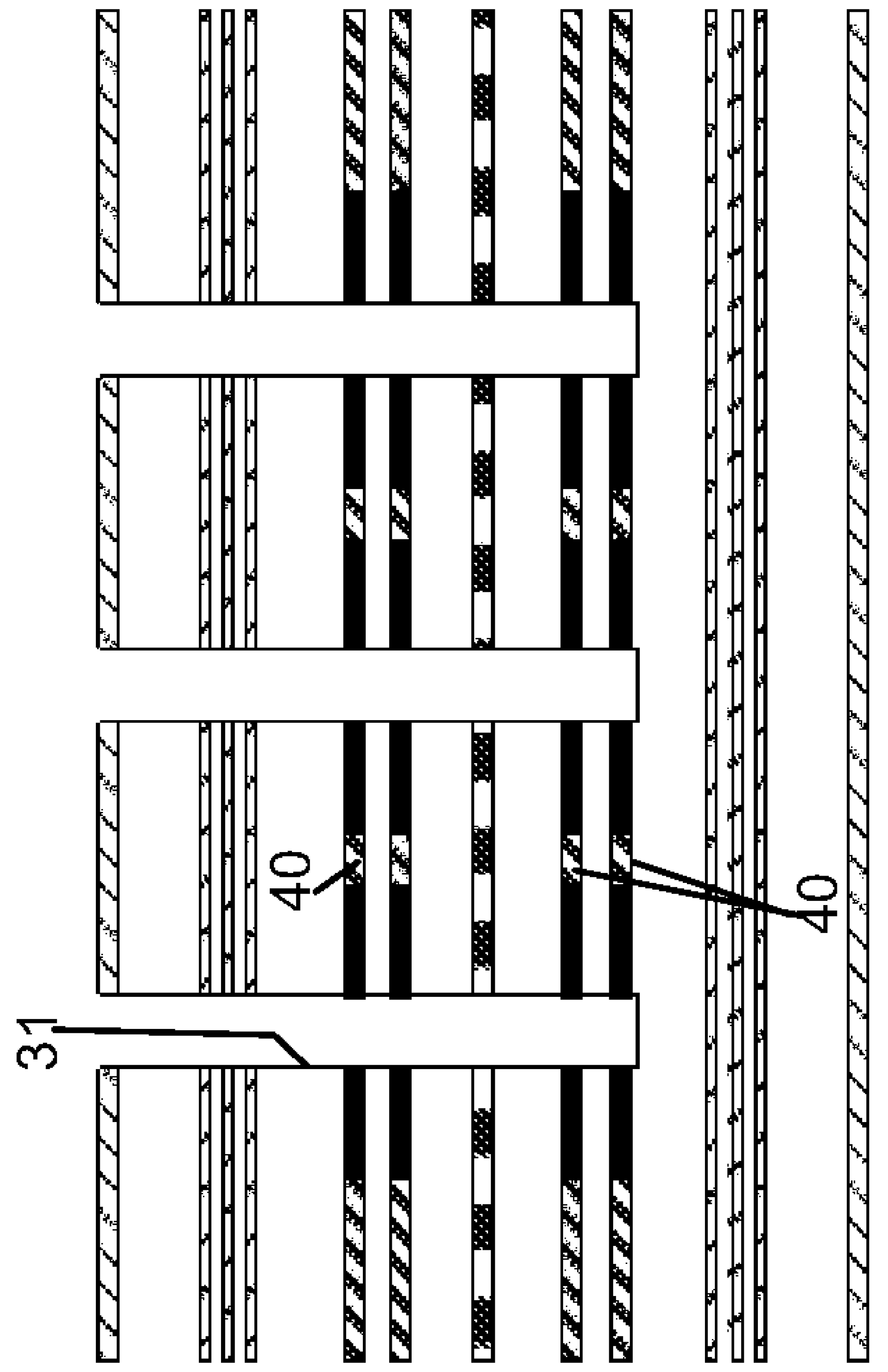


Fig. 14

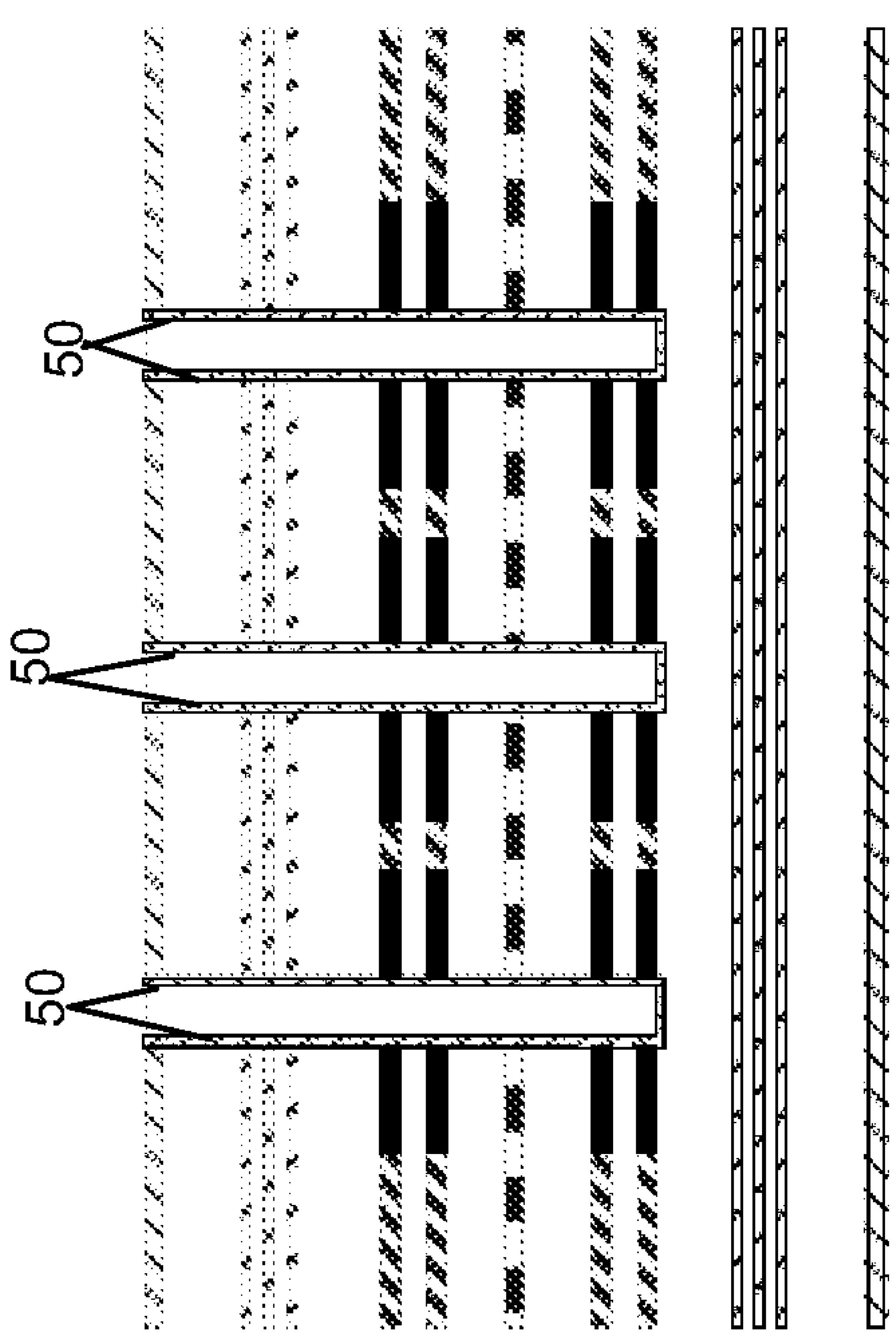


Fig. 15

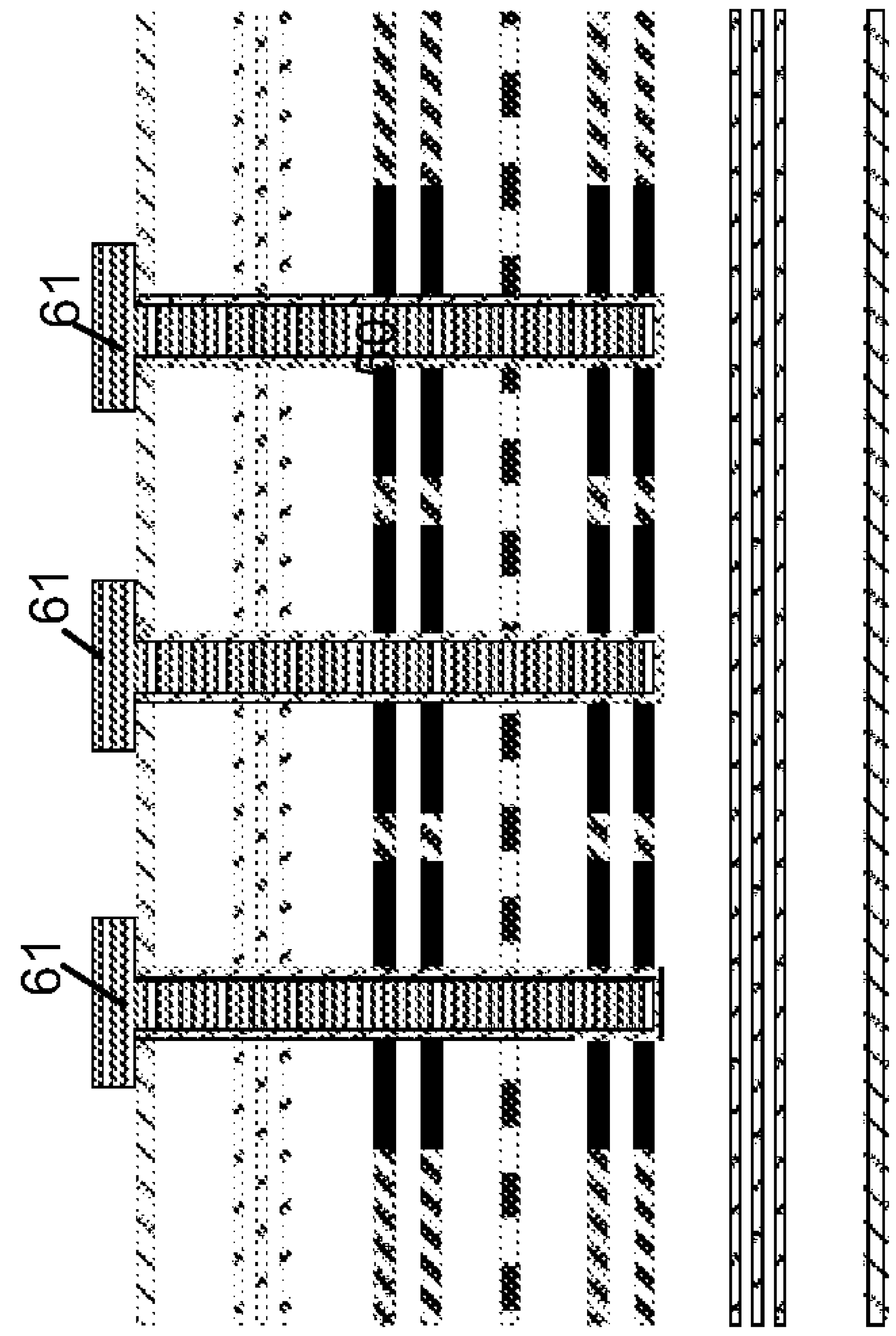


Fig. 16

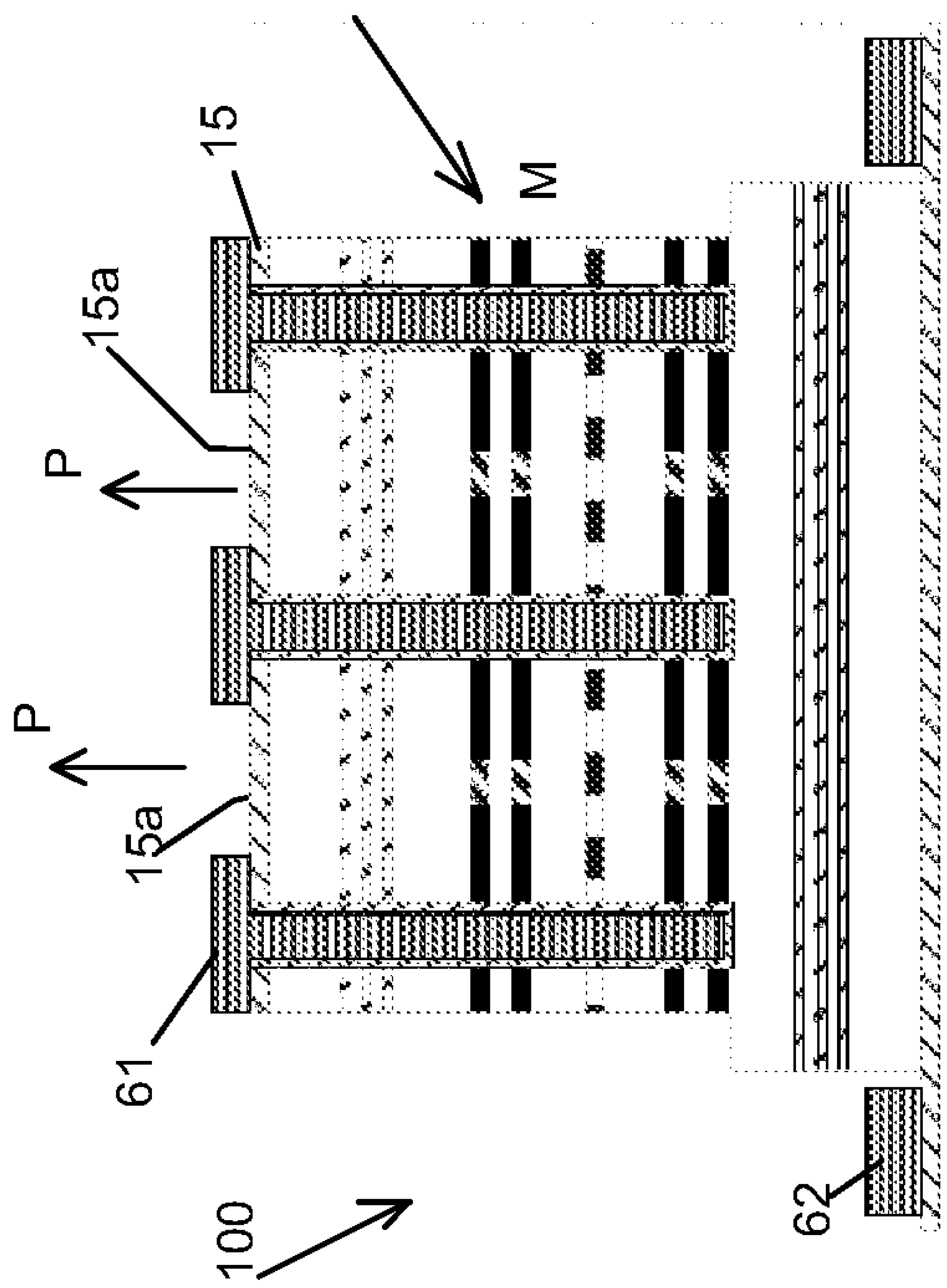


Fig. 18

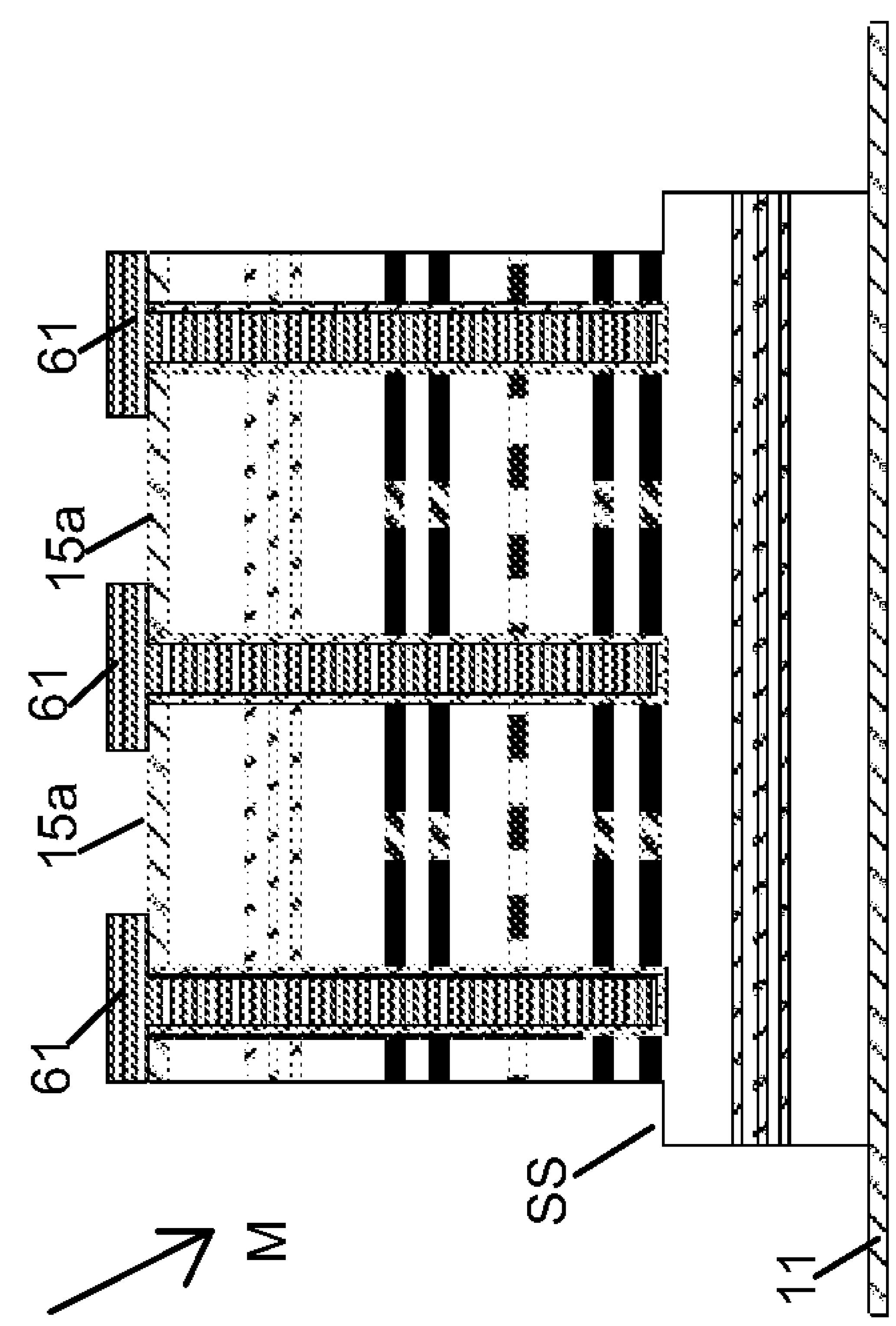


Fig. 17

RADIATION EMITTER

[0001] The present application claims the benefit of and priority to European Patent Application EP20192355 filed on Aug. 24, 2020 and European Patent Application EP21168265 filed on Apr. 14, 2021. The foregoing applications are incorporated by reference herein in their entirety.

BACKGROUND OF THE INVENTION

[0002] The energy required to transmit information as optical data bits within and between electronic and photonic integrated circuits, within and between computer servers, within and between data centers, and ultimately across the earth from one point to another spans from typically tens of picojoules-per-bit to well over tens of millijoules-per-bit for intercontinental distances. Internet use increases by 60%/year and larger and larger data centers (in size and energy consumption) with millions of optical interconnects are presently built. To keep up with the demand in communication capacity, data transmission across longer and longer distances using high power single mode emitters combined with dense wavelength multiplexing must be enabled.

[0003] Key enabling emitters for short distances up to 1-2 km are high power single mode vertical-cavity surface-emitting lasers (VCSELs).

[0004] VCSELs can be easily designed to emit at a variety of wavelengths across present multi- and single-mode optical cables for such short distances. Wavelength division multiplexing, WDM, increases enormously the bitrate per link.

[0005] Optimized combination of the number of channels and the bit rate reduces the energy consumption and operating cost of the network as shown by Larisch et al. (G. Larisch, S. Tian, and D. Bimberg, "Optimization of VCSEL photon lifetime for minimum energy consumption at varying bit rates," *Opt. Express, vol.* 28, p. 6, 2020). The IEEE 802.3cd standard defines a 30 nm spacing between "channels", a number adapted to properties of typical multimode VCSELs. A further enormous increase of bandwidth per link, necessary to catch-up with demand, in line with additional reduction of energy consumption can be achieved by further reducing the spacing between the wavelengths. Narrow emission spectra are necessary to avoid cross talk between the channels. A further advantage of such spectra is the reduction of dispersion, supporting additionally increases of the transmission distances, as discussed in the publication by Larisch et al. (G. Larisch, A. A. Juarez, X. Chen, K. Li, D. Bimberg, and M.-J. Li, "910 nm Single-Mode VCSELs and its Application for Few-Mode Transmission over Graded-Index Single-Mode Fibers (Invited)," in 2020 22 *nd International Conference on Transparent Optical Networks* (*ICTON*)).

[0006] Spectrally narrow emission is achieved today in particular by suppressing higher order modes of the laser. Higher order modes can be avoided by reduction of the size of the active area, leading to an increase of the D-factor:

$$f_R = D\sqrt{I - I_{th}}$$

[0007] With relaxation resonance frequency fR, current I and threshold current Ith.

$$D = \frac{1}{2\pi}\sqrt{\frac{\eta_i \Gamma v_g}{q} \cdot \frac{g'}{V_a}}$$

[0008] With g' differential gain, Va active volume, ηi internal quantum efficiency, vg group velocity, Γ confinement-Factor.

[0009] The size of the active area of a VCSEL depends on its cavity length and its aperture diameter. Today's datacom VCSELs usually have a cavity lengths of lambda half. A further reduction is not possible. A reduction of aperture diameter leads to several drawbacks. The resistance and the differential resistance increase, and the output power drops. A low electrical resistance eases however impedance match of laser and driver, and reduces the total energy consumption of present driver designs.

OBJECTIVE OF THE PRESENT INVENTION

[0010] In view of the above, an objective of the present invention is to propose radiation emitters that may provide large output powers with relatively small aperture diameters.

[0011] A further objective of the present invention is to provide a method for fabricating radiation emitters that provide large output powers with relatively small aperture diameters.

BRIEF SUMMARY OF THE INVENTION

[0012] A first exemplary embodiment of the present invention relates to a method of fabricating a radiation emitter comprising the steps of

- **[0013]** fabricating a layer stack that comprises a first reflector, an active region, an oxidizable layer, and a second reflector; and
- **[0014]** locally removing the layer stack, and thereby forming a mesa of the radiation emitter, wherein said mesa comprises the first reflector, the active region, the oxidizable layer and the second reflector,

[0015] wherein

[0016] before or after locally removing the layer stack and forming said mesa the following steps are carried out:

- **[0017]** vertically etching blind holes inside the layer stack, wherein the blind holes vertically extend at least to the oxidizable layer and expose the oxidizable layer; and
- **[0018]** oxidizing the oxidizable layer via the sidewalls of the blind holes in lateral direction, wherein from each hole an oxidation front radially moves outwards and wherein the etching is terminated before the entire oxidizable layer is oxidized, thereby forming at least two unoxidized apertures, each of which is limited by at least three oxidation fronts, inside the mesa.

[0019] An advantage of this embodiment of the invention is that the method allows fabricating mesas which each have a plurality of relatively small apertures, in contrast to mesas of prior art VCSELS. In prior art VCSELs, apertures are formed by oxidizing oxidizable layers after the mesa is etched, i.e. by oxidizing via the sidewall of the mesa. Therefore, the prior art fabrication can provide a single aperture per mesa, only. In contrast thereto and according to the invention, the apertures are formed (either before the mesa is etched or thereafter) by etching blind holes and oxidizing oxidizable layer or layers from the inside of the holes via the holes' sidewalls. This procedure allows creating apertures which are independent from the formation of the mesa. Therefore, it is possible to fabricate a plurality of apertures within the same mesa. For example, the resulting radiation emitter may have a plurality of densely spaced apertures which each define a VCSEL sub-cell or VCSEL subunit within the same mesa. The VCSEL sub-cells may operate in parallel and allow the mesa to output larger amounts of energy than mesas with a single aperture are capable of.

[0020] Said mesa is preferably provided with at least two individual VCSEL units by fabricating said at least two apertures within the same oxidizable layer.

[0021] The at least two apertures preferably form VCSEL sub-cells that operate in parallel.

[0022] The apertures are preferably so narrowly spaced in said mesa that the resulting radiation emitter provides single mode emission.

[0023] The radiation that the two apertures or VCSEL sub-cells generate, may differ with respect to each other. However, the difference is preferably smaller than 0.1% of the average wavelength.

[0024] Preferably, at least six blind holes are vertically etched inside the layer stack, wherein the blind holes vertically extend at least to the oxidizable layer and expose the oxidizable layer. By oxidizing the oxidizable layer via the sidewalls of the at least six blind holes in lateral direction the at least two apertures may be fabricated inside said same oxidizable layer.

[0025] Preferably, at least four apertures are fabricated within said same oxidizable layer.

[0026] Further, at least nine blind holes may be vertically etched inside the layer stack, wherein the blind holes vertically extend at least to the oxidizable layer and expose the oxidizable layer. By oxidizing the oxidizable layer via the sidewalls of the blind holes in lateral direction said at least four apertures may be fabricated within said same oxidizable layer.

[0027] A top contact layer is preferably fabricated on top of the second reflector.

[0028] The top contact layer is preferably provided with a first conducting material

- **[0029]** such that the conducting material partly covers the surface of the top contact layer, and
- **[0030]** such that sections of the top contact layer above the apertures are left uncovered in order to allow optical radiation to exit the mesa without additional attenuation.

[0031] Preferably, the steps of vertically etching the blind holes and oxidizing the oxidizable layer or layers via the sidewalls of the blind holes, are carried out before the mesa is etched.

[0032] The at least three blind holes per radiation emitter are preferably vertically etched inside the layer stack in an area which belongs to the at least one mesa after locally removing the layer stack.

[0033] Preferably, at least four blind holes are etched inside the layer stack in an area which will belong to the at least one mesa. At least one unoxidized aperture is preferably limited by at least four oxidation fronts.

[0034] A plurality of blind holes may be etched inside the layer stack in an area which will belong to the at least one mesa.

[0035] The blind holes are preferably arranged in a lattice-like way forming a grid having a first grid spacing in a first direction and a second grid spacing in a second different direction.

[0036] The first grid spacing and the second grid spacing may be identical, for instance in order to generate symmetrical apertures in view of an emission of polarization independent radiation.

[0037] Alternatively, the first grid spacing may be between 10% and 30% larger than the second grid spacing, for instance in order to generate asymmetrical apertures in view of an emission of polarization dependent radiation.

[0038] According to a preferred embodiment, a 3×3 grid having nine blind holes or a 4×4 grid having sixteen blind holes is formed per radiation emitter.

[0039] The oxidation may be carried out using processing parameters causing circular oxidation fronts, for instance in order to generate symmetrical apertures in view of an emission of polarization independent radiation.

[0040] Alternatively, the oxidation may be carried out using processing parameters causing anisotropic (e. g. elliptical) oxidation fronts, for instance in order to generate asymmetrical apertures in view of an emission of polarization dependent radiation.

[0041] The oxidized material of the oxidizable layer or layers is preferably electrically non-conductive.

[0042] Said step of fabricating the layer stack may include forming two or more oxidizable layers inside the layer stack.

[0043] In case that two or more oxidizable layers are fabricated within the layer stack, at least two of said oxidizable layers are preferably each provided with at least two apertures.

[0044] If the layer stack comprises two or more oxidizable layers, at least two apertures may be formed within each of the oxidizable layers.

[0045] In case of two or more oxidizable layers, stacks of vertically aligned apertures may be fabricated. Each of the vertical stacks of apertures in combination with the adjacent section of the active region may be regarded as an individual VCSEL unit within the radiation emitter. In other words, in the latter embodiment, two or more apertures may be located in the same plane ("horizontal" plane) and two or more planes may be stacked vertically in order to form a group (for instance a grid) of vertically stacked apertures.

[0046] The at least one oxidizable layer or at least one of the oxidizable layers may be formed between the first reflector and the active layer.

[0047] The at least one oxidizable layer or at least one of the oxidizable layers may be formed inside the first reflector.

[0048] The at least one oxidizable layer or at least one of the oxidizable layers may be formed between the second reflector and the active layer.

[0049] The at least one oxidizable layer or at least one of the oxidizable layers may be formed inside the second reflector.

[0050] In a preferred embodiment, at least one of the oxidizable layers is formed inside the first reflector or between the first reflector and the active layer and at least one of the oxidizable layers is formed inside the second reflector or between the second reflector and the active layer.

[0051] In another preferred embodiment, at least two oxidizable layers are formed inside the first reflector or between the first reflector and the active layer and/or at least two oxidizable layers are formed inside the second reflector or between the second reflector and the active layer.

[0052] The method described above is preferably carried out in a wafer-scale fashion wherein a plurality of mesas (and therefore emitters), which each comprise a plurality of apertures, is fabricated simultaneously.

[0053] A second exemplary embodiment of the present invention relates to a radiation emitter comprising a layer stack having a first reflector, an active region, at least two apertures formed by unoxidized material of an oxidizable layer that is partly oxidized and partly unoxidized, and a second reflector;

[0054] wherein a mesa of the emitter includes at least the first reflector, the active region, the oxidizable layer and the at least two apertures, and the second reflector,

[0055] wherein the mesa further comprises at least three blind holes which vertically extend to oxidized sections of the oxidizable layer, and

[0056] wherein the at least two apertures are each limited by oxidation fronts of at least three of said oxidized sections, and

[0057] wherein each of the blind holes forms a center point of one of the oxidation fronts.

[0058] The at least two apertures preferably form VCSEL sub-cells that operate in parallel, inside said same mesa.

[0059] The apertures are preferably so narrowly spaced in said mesa that the resulting radiation emitter provides single mode emission. The radiation that the two apertures or VCSEL sub-cells generate, may differ with respect to the radiation wavelength. However, the difference is preferably smaller than 0.1% of the average wavelength.

[0060] At least five blind holes are preferably located inside said mesa.

[0061] At least four apertures are preferably located within said mesa.

[0062] A top contact layer is preferably located on top of the second reflector.

[0063] A first conducting material is preferably located on top of the top contact layer, wherein the conducting material partly covers the surface of the top contact layer, but leaves sections of the top contact layer above the apertures uncovered in order to allow optical radiation to exit the mesa without additional attenuation.

[0064] The blind holes are preferably filled with a conducting material or at least the sidewalls of the holes are covered with the conducting material. The conducting material is preferably thermally conductive in order to dissipate heat that is generated during the operation of the radiation emitter.

[0065] The conducting material may also be electrically conductive, for instance in order to bypass electrical current.

[0066] The sidewalls of the blind holes and the conducting material or at least a section thereof may form an ohmic contact with the layer stack.

[0067] The conducting material or at least a section thereof may be isolated from the sidewalls of the blind holes and/or the bottom of the blind holes by an intermediate isolating layer, for instance to block a bypass of electrical current.

[0068] The at least one aperture or at least one of the apertures may be subjected to electrical current flow as well as optical radiation when the radiation emitter operates.

[0069] The conducting material may form an electrical bypass with respect to at least one of the apertures. Each bypassed aperture is subjected to optical radiation, only, because electrical current bypasses the bypassed aperture via the corresponding bypass.

[0070] Two or more apertures may be located inside the second reflector and/or between the active region and the second reflector.

[0071] At least the aperture that is the most adjacent to the active region, may be subjected to electrical current flow as well as optical radiation when the radiation emitter operates, wherein at least one of the remaining apertures may be bypassed.

[0072] A third exemplary embodiment of the present invention relates to a method of fabricating at least one radiation emitter comprising the steps of

[0073] fabricating a layer stack that comprises a first reflector, an active region, an oxidizable layer, and a second reflector; and

[0074] locally removing the layer stack, and thereby forming at least one mesa, wherein the at least one mesa comprises the first reflector, the active region, the oxidizable layer and the second reflector,

[0075] characterized in that

[0076] before or after locally removing the layer stack and forming the at least one mesa the following steps are carried out:

[0077] vertically etching at least three blind holes per radiation emitter inside the layer stack, wherein the blind holes vertically extend at least to the oxidizable layer and expose the oxidizable layer; and

[0078] oxidizing the oxidizable layer via the sidewalls of the blind holes in lateral direction, wherein from each hole an oxidation front radially moves outwards and wherein the etching is terminated before the entire oxidizable layer is oxidized, thereby forming at least one unoxidized aperture that is limited by at least three oxidation fronts, per radiation emitter.

[0079] The features, including the optional and/or beneficial features, discussed above with reference to the first and second exemplary embodiment of the present invention may be implemented in or combined with the third exemplary embodiment of the present invention in order to create beneficial variants (or configurations) of the third exemplary embodiment of the present invention.

[0080] A fourth exemplary embodiment of the present invention relates to a radiation emitter (for instance a VCSEL) comprising

[0081] a layer stack having a first reflector, an active region, at least one aperture formed by unoxidized material of an oxidizable layer that is partly oxidized and partly unoxidized, and a second reflector;

[0082] wherein a mesa of the emitter includes at least the first reflector, the active region, the oxidizable layer, and the second reflector,

[0083] characterized in that

[0084] the mesa further comprises at least three blind holes which vertically extend to oxidized sections of the oxidizable layer,

[0085] wherein the at least one aperture is limited by oxidation fronts of at least three oxidized sections, and

[0086] wherein each of the blind holes forms a center point of one of the oxidation fronts.

[0087] The features, including the optional and/or beneficial features, discussed above with reference to the first and second exemplary embodiment of the present invention may be implemented in or combined with the fourth exemplary embodiment of the present invention in order to create beneficial variants (or configurations) of the fourth exemplary embodiment of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0088] In order that the manner, in which the above-recited and other advantages of the invention are obtained, will be readily understood, a more particular description of the invention briefly described above will be rendered by reference to specific embodiments thereof, which are illustrated in the appended figures. Understanding that these figures depict only typical embodiments of the invention and are therefore not to be considered limiting of its scope, the invention will be described and explained with additional specificity and detail by the use of the accompanying drawings in which

[0089] FIGS. **1-12** illustrate method steps for fabricating an exemplary embodiment of a radiation emitter in the form of a VCSEL, and

[0090] FIGS. **13-18** illustrate method steps for fabricating another exemplary embodiment of a radiation emitter in the form of a VCSEL.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0091] The preferred embodiments of the present invention will be best understood by reference to the drawings, wherein identical or comparable parts are designated by the same reference signs throughout.

[0092] It will be readily understood that the parameters of the embodiments of the present invention, as generally described herein, could vary in a wide range. Thus, the following more detailed description of exemplary embodiments of the present invention, is not intended to limit the scope of the invention but is merely representative of presently preferred embodiments of the invention.

[0093] FIGS. **1-12** show method steps for fabricating an exemplary embodiment of a radiation emitter in the form of a VCSEL **100** (see FIG. **7**).

[0094] FIG. **1** shows a cross-section of an exemplary layer stack **10** that comprises a first (lower) contact layer **11**, a first reflector **12**, an active region **13**, a first (lower) oxidizable layer **21**, a second (upper) oxidizable layer **22**, a second reflector **14**, and a second (top) contact layer **15**.

[0095] The first contact layer **11** is preferably highly p-doped (doping level>10^{19} cm^{-3}). The second contact layer **15** is preferably highly n-doped (doping level>10^{19} cm^{-3}).

[0096] The first and second reflectors **12** and **14** may be distributed Bragg reflectors (DBRs) that each comprise a plurality of reflector layers with alternating reflective indices.

[0097] The layer stack **10** is preferably fabricated by depositing semiconductor material such as AlGaAs on a substrate **10***a*.

[0098] In the exemplary embodiment of FIG. **1**, the two oxidizable layers **21-22** are located above the active region **13**.

[0099] FIG. **2** shows the layer stack **10** of FIG. **1** after vertically etching blind holes **30** inside the layer stack **10**. The blind holes **30** vertically protrude to the oxidizable layers **21-22** and expose the oxidizable layers **21-22**.

[0100] FIG. **3** shows the layer stack **10** of FIG. **2** after oxidizing the oxidizable layers **21-22** via the sidewalls **31** of the blind holes **30** in lateral direction. From each blind hole **30**, an oxidation front radially (see arrow R) moves outwards during the oxidation. The step of etching is terminated before the entire oxidizable layers **21-22** are oxidized in order to form unoxidized apertures **40**. Each unoxidized aperture **40** is limited by at least three oxidation fronts of oxidized layer material **20**. The oxidized layer material **20** is preferably electrically isolating.

[0101] FIG. **4** shows the layer stack **10** of FIG. **3** after depositing an intermediate isolating layer **50** on the bottom and the lower section of the blind holes **30**. The intermediate isolating layer **50** covers the edges of the oxidized layer material **20** of the first oxidizable layer **21**.

[0102] FIG. **5** shows the layer stack **10** of FIG. **4** after filling the blind holes **30** with a first conducting material **61**. The first conducting material **61** is preferably electrically and thermally conductive. The conducting material **61** is preferably Gold, Platinum, Titanium, Nickel, Gold-Germanium alloy or a sequence of these materials, depending on the doping type of the semiconductor material that is to be contacted.

[0103] In the embodiment of FIG. **5**, the first conducting material **61** forms an ohmic contact with the uncovered sidewalls **31** of the blind holes **30**.

[0104] Since the intermediate isolating layer **50** does not cover the edges of the oxidized layer material **20** of the second oxidizable layer **22**, the apertures **40** formed in the second oxidizable layer **22** are electrically bypassed. This means that electrical current that is applied during the operation of the resulting radiation emitter **100** (see FIG. **7**) after completing the fabrication, may flow from the surface of the layer stack **10** through the conducting material **61** into the layer or layers that are located between the first and second oxidizable layers **21-22**.

[0105] Since the intermediate isolating layer **50** covers the edges of the oxidized layer material **20** of the first oxidizable layer **21**, the apertures **40** formed in the first oxidizable layer **21** are not electrically bypassed. This means that electrical current is forced to pass the apertures **40** that are located in the first oxidizable layer **21**.

[0106] In addition to its electrical influence, the first conducting material **61** preferably forms a heat sink that dissipates heat during the operation of the resulting radiation emitter **100**.

[0107] The conducting material **61** may partly cover the surface of the second contact layer **15**. However, sections **15***a* of the second contact layer **15** above the apertures **40** are preferably left uncovered in order to allow optical radiation P to exit the radiation emitter **100** without additional attenuation.

[0108] FIG. **6** shows the layer stack **10** of FIG. **5** after etching a mesa M inside the layer stack **10**. The mesa M may have one or more steps SS. The mesa M preferably extends to the first contact layer **11** in order to allow depositing a second conductive material **62** and thereby contacting the first contact layer **11**.

[0109] FIG. **7** shows the layer stack **10** of FIG. **6** after depositing the second conductive material **62** and contacting the first contact layer **11**. The layer stack **10** of FIG. **7** provides a radiation emitter in the form of a VCSEL **100**.

[0110] When applying an electrical voltage between the first and second conducting material **61** and **62**, electrical current will flow through the apertures **40** of the first oxidizable layer **21** and the active region **13**. The active region **13** generates optical radiation P that exits the radiation emitter **100** through the surface sections **15***a* of the second contact layer **15** that is uncovered by the first conductive material **61**.

[0111] Each of the apertures **40** in combination with the adjacent section of the active region **13** may be regarded as an individual VCSEL unit within the radiation emitter **100** that comprises a plurality of these individual VCSEL units.

[0112] FIG. **8** shows a top view of the layer stack **10** of FIG. **2**. after etching the blind holes **30** (for instance nine blind holes as depicted in FIG. **8**). The nine blind holes **30** are preferably arranged in a lattice-like way forming a grid having a first grid spacing d**1** in a first direction D**1** and a second grid spacing d**2** in a second different direction D**2**.

[0113] In one preferably embodiment, the first grid spacing d**1** and the second grid spacing d**2** are identical. In another preferably embodiment, the first grid spacing d**1** is between 10% and 30% larger than the second grid spacing d**2**.

[0114] The first and second direction D**1**, D**2** can be perpendicular. Alternatively, the first and second direction D**1**, D**2** may be angled, preferably with an angle between 60° and 85°.

[0115] FIG. **9** shows a top view of the layer stack **10** of FIG. **3** after oxidizing the oxidizable layers **21-22**. From each blind hole **30**, an oxidation front **32** radially moves outwards during the oxidation. Each unoxidized aperture **40** is limited by four oxidation fronts **32** of oxidized layer material **20** and therefore has a diamond-like shape. As depicted in FIGS. **9-11**, the nine blind holes will lead to four apertures **40** in each of the two oxidizable layers **21** and **22**. Each of the four vertical stacks of apertures **40** will be part of a future VCSEL subunit or subcell.

[0116] FIG. **10** shows a top view of the layer stack **10** of FIG. **5** after filling the blind holes **30** with the first conductive material **61**. Sections **15***a* of the second contact layer **15** above the apertures **40** are left uncovered in order to allow the optical radiation P to exit the VCSEL subunits of the radiation emitter **100**.

[0117] FIG. **11** shows a top view of the layer stack **10** of FIG. **7**, i.e. the resulting radiation emitter **100** after contacting the first contact layer **11** by depositing the second conductive material **62**.

[0118] In the exemplary embodiment of FIGS. **1-11**, the layer stack **10** comprises two oxidizable layers **21** and **22**. Therefore, four stacks, each of which comprises two vertically aligned apertures **40**, are fabricated within each mesa M. Each of the four vertical stacks of apertures **40** in combination with the adjacent section of the active region **13** may be regarded as an individual VCSEL subunit within the radiation emitter **100**.

[0119] FIGS. **12-18** show method steps for fabricating another exemplary embodiment of a radiation emitter in the form of a VCSEL **100**.

[0120] FIG. **12** shows a cross-section of an exemplary layer stack **10** that comprises four oxidizable layers **21-24**. Two oxidizable layers **21-22** are located below the active region **13**, and two oxidizable layers **23-24** are located above the active region **13**.

[0121] FIG. **13** shows the layer stack **10** of FIG. **1** after vertically etching blind holes **30** inside the layer stack **10**. The blind holes **30** vertically extend to the lowest oxidizable layer **21** and expose all of the oxidizable layers **21-24**.

[0122] FIG. **14** shows the layer stack **10** of FIG. **13** after oxidizing the oxidizable layers **21-24** via the sidewalls **31** of the blind holes **30** in lateral direction. From each hole, an oxidation front radially moves outwards during the oxidation. The step of etching is terminated before the entire oxidizable layer is oxidized in order to form unoxidized apertures **40**. Each unoxidized aperture **40** is limited by at least three oxidation fronts of oxidized layer material.

[0123] FIG. **15** shows the layer stack **10** of FIG. **14** after depositing an intermediate isolating layer **50** on the bottom and the entire sidewalls **31** of the blind holes **30**.

[0124] FIG. **16** shows the layer stack **10** of FIG. **15** after filling the blind holes **30** with a first conducting material **61**. The conducting material **61** is preferably electrically and thermally conductive. The conducting material **61** is preferably Gold, Platinum, Titanium, Nickel, Gold-Germanium alloy or a sequence of these materials, depending on the doping type of the semiconductor material that is to be contacted.

[0125] Since the intermediate isolating layer **50** covers the sidewalls **31** of the blind holes **30**, none of the apertures **40** is electrically bypassed. This means that electrical current that is applied during the operation of the resulting radiation emitter **100** after completing the fabrication, flows through all of the apertures **40**.

[0126] FIG. **17** shows the layer stack **10** of FIG. **16** after etching a mesa M inside the layer stack **10**. The mesa M may have one or more steps SS. The mesa M preferably extends to the first contact layer **11** in order to allow depositing a second conductive material **62** and contacting the first contact layer **11**.

[0127] FIG. **18** shows the layer stack **10** of FIG. **17** after depositing the second conductive material **62** and contacting the first contact layer **11**. The layer stack **10** of FIG. **18** provides a radiation emitter in the form of a VCSEL **100**.

[0128] In the embodiment of FIGS. **12-18**, the layer stack **10** comprises four oxidizable layers **21-24**. Therefore, four stacks, each of which comprises four vertically aligned apertures **40**, are fabricated within each mesa M. Each of the four vertical stacks of apertures **40** in combination with the adjacent section of the active region **13** may be regarded as an individual VCSEL subunit within the radiation emitter **100**.

[0129] In FIG. **18**, the vertical arrows indicate the radiation P that is emitted by the four individual VCSEL subunits that are each formed by a vertical stack of apertures **40** in combination with the adjacent section of the active region **13**.

[0130] When applying an electrical voltage between the first and second conducting material **61**,**62**, electrical current will flow through the apertures **40** of all oxidizable layers **21-22**. The active region **13** generates optical radiation that exits the radiation emitter **100** through the surface sections **15***a* of the second conducting layer **15** that is uncovered by the first conductive material **61**. Each of the apertures **40** (or each of the vertical stacks of apertures **40**) in combination with the adjacent section of the active region **13** may be regarded as an individual VCSEL unit within the radiation emitter **100** that comprises a plurality of these individual VCSEL units.

[0131] In summary the exemplary embodiments described above relate to a method for fabricating a vertical-cavity surface-emitting laser (VCSEL) as radiation emitter **100** with multiple apertures **40** narrowly spaced in a single mesa M that result in single mode emission together with large optical output power and small electrical resistance. The fabrication of the VCSEL **100** may be based on etching of narrow holes **30**, e.g. 5 μm or less, in a regular array of a few μm distance between each hole into VCSEL wafers containing for instance AlGaAs (preferentially about 98% Al-contents) aperture layers. The arrangement of the holes **30** with respect to each other is variable and application dependent. The oxidation of the e.g. AlO apertures **40** is progressing from the inside of the holes **30**. The orientation of the axes of the hole-arrays can be varied with respect to the crystal axes, thus leading to self-limiting orientation dependent oxidation processes. The novel VCSEL properties, including defined polarization, enable data transmission across large fiber distances ~1 km and more, as well as dense wavelength division multiplexing (≤15 nm spacing). In addition, impedance matching of laser and driver circuits is eased due to the reduced impedance of the invention.

[0132] The exemplary embodiments of the invention described above may have one or more of the following features and/or advantages:

[0133] Exemplary embodiments of the invention may relate to a method for fabricating a vertical-cavity surface-emitting laser (VCSEL) with multiple apertures narrowly spaced in a single mesa M that result in single mode emission together with large optical output power and small electrical resistance.

[0134] Exemplary embodiments of the invention may consist of an active region sandwiched between two distributed Bragg reflectors (DBRs) and at least one oxid layer like a "normal" VCSEL structure. Any presently existing epi structure for high-speed oxide confined VCSELs can be used for the inventive approach. In contrast to presently employed VCSEL processing, the oxidation process may be based on etching holes of any shape into the wafer surface, exposing the oxide layer(s). These holes are serving as starting point for the lateral oxidation process.

[0135] The speed of the wet oxidation of the oxidizable layer(s) **21-24** may depend on Al-contents, AlGaAs layer thickness, and most importantly on the crystallographic direction. In addition it is controlled by temperature, total pressure and water partial pressure.

[0136] The arrangement of the etched holes in respect to each other and to the crystal axes, the distances between them, and finally the choice of the oxidation parameters impacts the shape of the resulting apertures and opens up new design roads. The oxidation fronts may be circular or elliptical. The resulting apertures may have a diamond shape.

[0137] The final processing step may comprise mesa M etching, re-contact deposition, and planarization based on the processing steps developed for "normal" VCSELs.

[0138] GaAs/AlAs heterostructures are enabling the growth of lattice matched DBRs and high Al-content layers suitable for wet oxidation and leading to current and optical field confinement. The apertures will not be oxidized from the outside after etching a mesa M, but from the inside of holes, being first of all etched in regular arrays.

[0139] The arrangement of the blind holes with respect to each other and to the crystal axes presents a free design parameter. The resulting apertures however may have always the same size. A difference in distance of the holes in one direction and the other direction may lead to a difference in oxide diameter in both directions and may allow polarized emission if desired.

[0140] The oxidation speed depends on the crystal axes. The impact on the shape of the oxidation front has an impact on the shape of the resulting apertures.

[0141] The alignment between the series of holes defined by the mask and the crystal axes may enable a shape optimization of the oxide confined apertures and allows to control the polarization status of the emitted light.

[0142] The distances between the holes (d**1** in one direction and d**2** in the other direction) and the size of the holes can be chosen to position a sufficient number of apertures so close to each other, that additionally the emitted light emission can be coupled into the 50 or 62.5 μm core of a multimode fiber (MMF) preferably without coupling optics.

[0143] The optical power increases linearly with the number of apertures. If the size of the apertures is chosen in such a way that the laser emits single mode light, it intensity increases with the number of apertures, showing identical wavelength, polarization and transversal mode. The electrical resistance decreases similarly with the number of apertures. The total resistance Rt can be calculated by

$$\frac{1}{R_t} = \sum_{x=1}^{n} \frac{1}{R_x}$$

[0144] With the resistance Rx of an individual aperture.

[0145] The various embodiments and aspects of embodiments of the invention disclosed herein are to be understood not only in the order and context specifically described in this specification, but to include any order and any combination thereof. Whenever the context requires, all words used in the singular number shall be deemed to include the plural and vice versa. Whenever the context requires, all options that are listed with the word "and" shall be deemed to include the word "or" and vice versa, and any combination thereof.

[0146] In the drawings and specification, there have been disclosed a plurality of embodiments of the present invention. The applicant would like to emphasize that each feature of each embodiment may be combined with or added to any other of the embodiments in order to modify the respective embodiment and create additional embodiments. These additional embodiments form a part of the present disclosure and, therefore, the applicant may file further patent claims regarding these additional embodiments at a later stage of the prosecution.

[0147] Further, the applicant would like to emphasize that each feature of each of the following dependent claims may be combined with any of the present independent claims as well as with any other (one ore more) of the present dependent claims (regardless of the present claim structure).

Therefore, the applicant may direct further patent claims towards other claim combinations at a later stage of the prosecution.

1. Method of fabricating a radiation emitter (**100**) comprising the steps of

fabricating a layer stack (**10**) that comprises a first reflector (**12**), an active region (**13**), an oxidizable layer (**21-24**), and a second reflector (**14**); and

locally removing the layer stack (**10**), and thereby forming a mesa (M) of the radiation emitter (**100**), wherein said mesa (M) comprises the first reflector (**12**), the active region (**13**), the oxidizable layer (**21-24**) and the second reflector (**14**),

wherein

before or after locally removing the layer stack (**10**) and forming said mesa (M) the following steps are carried out:

vertically etching blind holes (**30**) inside the layer stack (**10**), wherein the blind holes (**30**) vertically extend at least to the oxidizable layer (**21-24**) and expose the oxidizable layer (**21-24**); and

oxidizing the oxidizable layer (**21-24**) via the sidewalls (**31**) of the blind holes (**30**) in lateral direction, wherein from each hole an oxidation front (**32**) radially moves outwards and wherein the etching is terminated before the entire oxidizable layer (**21-24**) is oxidized, thereby forming at least two unoxidized apertures, (**40**) each of which is limited by at least three oxidation fronts (**32**), inside the mesa.

2. Method of claim **1** wherein

said mesa is provided with at least two individual VCSEL units by fabricating said at least two apertures within said mesa and within the same oxidizable layer (**21-24**).

3. Method of claim **1** wherein

the at least two apertures form VCSEL sub-cells that operate in parallel.

4. Method of claim **1** wherein

the apertures (**40**) are so narrowly spaced in said mesa (M) that the resulting radiation emitter provides single mode emission.

5. Method of claim **1** wherein

at least six blind holes (**30**) are vertically etched inside the layer stack (**10**), wherein the blind holes (**30**) vertically extend at least to the oxidizable layer (**21-24**) and expose the oxidizable layer (**21-24**); and

by oxidizing the oxidizable layer (**21-24**) via the sidewalls (**31**) of the at least six blind holes (**30**) in lateral direction the at least two apertures are fabricated.

6. Method of claim **1** wherein

at least four apertures are fabricated within said mesa.

7. Method of claim **1** wherein

at least nine blind holes (**30**) are vertically etched inside the layer stack (**10**), wherein the blind holes (**30**) vertically extend at least to the oxidizable layer (**21-24**) and expose the oxidizable layer (**21-24**); and

by oxidizing the oxidizable layer (**21-24**) via the sidewalls (**31**) of the blind holes (**30**) in lateral direction said at least four apertures are fabricated.

8. Method of claim **1** wherein

a top contact layer (**15**) is fabricated on top of the second reflector (**14**), and

the top contact layer (**15**) is provided with a first conducting material (**61**) such that the conducting material (**61**) partly covers the surface of the top contact layer (**15**) and sections (**15***a*) of the top contact layer (**15**) above the apertures (**40**) are left uncovered in order to allow optical radiation (P) to exit the mesa (M) without additional attenuation.

9. Method according to claim **1** wherein

at least four blind holes (**30**) are etched inside the layer stack (**10**) and

at least one unoxidized aperture (**40**) is formed that is limited by at least four oxidation fronts (**32**).

10. Method according to claim **1** wherein

a plurality of blind holes (**30**) is etched inside the layer stack (**10**),

wherein the blind holes (**30**) are arranged in a lattice-like way forming a grid having a first grid spacing (d**1**) in a first direction (D**1**) and a second grid spacing (d**2**) in a second different direction (D**2**).

11. Method according to claim **1** wherein

the oxidation is carried out using processing parameters causing circular oxidation fronts (**32**) or

the oxidation is carried out using processing parameters causing anisotropic oxidation fronts (**32**).

12. Radiation emitter (**100**) comprising

a layer stack (**10**) having a first reflector (**12**), an active region (**13**), at least two apertures (**40**) formed by unoxidized material (**20**) of an oxidizable layer (**21-24**) that is partly oxidized and partly unoxidized, and a second reflector (**14**);

wherein a mesa (M) of the emitter (**100**) includes at least the first reflector (**12**), the active region (**13**), the oxidizable layer (**21-24**) and the at least two apertures (**40**), and the second reflector (**14**),

wherein the mesa (M) further comprises at least three blind holes (**30**) which vertically extend to oxidized sections of the oxidizable layer (**21-24**), and

wherein the at least two apertures (**40**) are each limited by oxidation fronts (**32**) of at least three of said oxidized sections, and

wherein each of the blind holes (**30**) forms a center point of one of the oxidation fronts (**32**).

13. Radiation emitter (**100**) of claim **12**

wherein the at least two apertures form VCSEL sub-cells that operate in parallel.

14. Radiation emitter (**100**) of claim **12**

wherein the apertures (**40**) are so narrowly spaced in said mesa (M) that the resulting radiation emitter provides single mode emission.

15. Radiation emitter (**100**) of claim **12** wherein at least five blind holes (**30**) are located inside said mesa.

16. Radiation emitter (**100**) of claim **12** wherein at least four apertures are located within said mesa.

17. Radiation emitter (**100**) of claim **12**,

wherein a top contact layer (**15**) is located on top of the second reflector (**14**),

wherein a first conducting material (**61**) is located on top of the contact layer (**15**),

wherein the conducting material (**61**) partly covers the surface of the second contact layer (**15**) and

wherein sections (**15***a*) of the second contact layer (**15**) above the apertures (**40**) are uncovered in order to allow optical radiation (P) to exit the mesa (M) without additional attenuation.

18. Radiation emitter (**100**) of claim **17** wherein

the blind holes (**30**) are filled with the conducting material (**61**) or at least the sidewalls (**31**) of the holes (**30**) are covered with the conducting material (**61**).

19. Radiation emitter (**100**) of claim **18**

wherein the conducting material forms an electrical bypass with respect to at least one of the apertures (**40**), and

wherein each bypassed aperture (**40**) is subjected to optical radiation (P), only, because electrical current bypasses the bypassed aperture (**40**) via the corresponding bypass.

20. Radiation emitter (**100**) of claim **19**

wherein two or more apertures (**40**) are located inside the second reflector (**14**) and/or between the active region (**13**) and the second reflector (**14**);

wherein at least the aperture (**40**) that is the most adjacent to the active region (**13**), is subjected to electrical current flow as well as optical radiation (P) when the radiation emitter (**100**) operates, and

wherein at least one of the remaining apertures (**40**) is bypassed.

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