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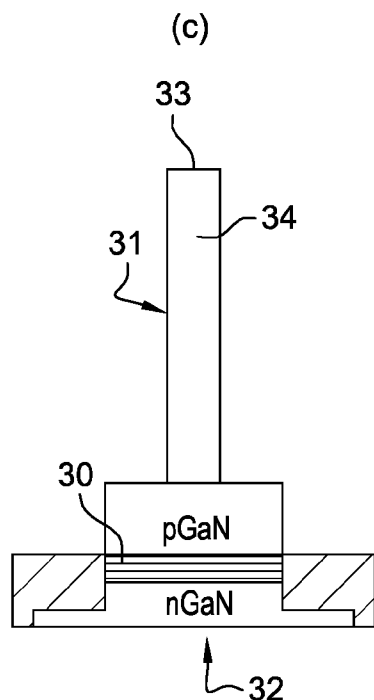


Fig. 3

(57) Abstract: The optoelectronic device contains a matrix of opto-
electronic components including semiconductor optical amplifiers
SOAs, the said semiconductor optical amplifiers SOAs containing an
active layer of gallium nitride GaN having multiple InGaN/GaAsN
or InGaN/AlGaIn quantum wells on a substrate of p-doped gallium
nitride and covered with a layer of n-doped gallium nitride. The p-
doped gallium nitride Ga N substrate forms a column of p-Ga N
covered with a layer of an insulator in biocompatible material. The
device can contain a matrix having multiple electronic components
of different heights. The optoelectronic component can be aphodi-
ode or a semiconductor optical amplifier SOA. This optoelectronic
device can be used in epiretinal or subretinal prostheses. A single
epiretinal or subretinal prosthesis can contain a matrix of photodi-
odes and a matrix of semiconductor optical amplifiers SOAs.



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OPTOELECTRONIC DEVICE

FIELD

This invention concerns the field of implantable optoelectronic devices that can be used in particular in retinal prostheses designed to offset the deterioration of the photoreceptor cells of the human eye.

BACKGROUND

The human eye, or eyeball, is a hollow structure with a globally spherical form. The innermost layer of the back part of the eye is the retina. The retina is a nervous structure, comprising many photoreceptors and neurones that process and channel visual information to the brain via the optic nerve. At the point where the optic nerve comes out, the retina is interrupted: this is the blind spot, close to which is the yellow spot, or macula, containing a central pit, known as the fovea.

Specialised photoreceptor nerve cells line the inner wall of the back of the eye; cones and rods, thus named due to their shape, which contain photo-sensitive substances. The rods, sensitive to light intensity, are photoreceptors that are designed specifically for twilight vision and the cones, responsible for colour vision, are designed more specifically for daylight vision. Cones are divided into three families of cells, each with its sensitivity peak in a determined zone of the spectrum (blue-purple, green and yellow-green).

The deterioration of the photoreceptor cells of the human eye may be due for example to age-related macular degeneration (AMD) or to genetically inherited retinitis pigmentosa. The photoreceptors (cones and rods) are the cells of the retina that are sensitive to light, whereas the other neurones that process signals captured by photoreceptors send information to the brain via the optic nerve. When photoreceptor cells deteriorate, the retina can no longer respond to light. However, a sufficient number of other neurones remain so that their electrical stimulation produces the perception of light by the brain.

In order to treat the deficiencies of the photoreceptor cells, two methods have been explored: implanting retinal prostheses and the optogenetic approach.

The optogenetic technique involves changing the neurones to make them sensitive to light, by incorporating a light-sensitive protein into the cellular membrane. By making each cell sensitive to light, vision can potentially be restored to near-normal acuity. However, artificial vision based on the optogenetic approach presents a major drawback. The modified cells require blue (460 nm) and very bright light to be activated, and the light intensity required is around seven times greater than the light sensitivity threshold normally observed in healthy individuals.

Retinal prostheses have an optoelectronic device that includes a matrix of optoelectronic components that are activated, either by light entering the eye in the case of a "subretinal" prosthesis, or by an electric signal from a micro-camera fitted outside the eye, in the case of an "epiretinal" prosthesis. The different types of implants used require a silicon-based technology which is easy to use and allows the development of nanometric devices. However silicon is a material that is opaque in the visible optic field.

The epiretinal solution involves placing an electronic implant in the front of the retina to stimulate the neurones. The epiretinal implant itself is not sensitive to light and must be connected to a micro-camera fitted outside the eye. The epiretinal implant requires a "coder" whose function is to fulfil the role of the neurones in the inner layer of the retina, which perform the preliminary processing of visual information.

In the United States, in February 2013 the Food and Drug Administration (FDA) authorised the use of the first epiretinal prosthesis designed to treat patients with advanced retinitis pigmentosa. This epiretinal prosthesis known as the "Argus II Retinal Prosthesis System" is manufactured by the company Second Sight Medical Products Inc. This epiretinal prosthesis is a gold standard with a matrix of some sixty electrodes, and has already been tested on patients throughout the world.

The sub-retinal prosthesis is placed beneath the retina to replace the destroyed photoreceptor nerve cells, which is surgically more difficult to perform but allows the neurones to be stimulated in a more natural position. The subretinal prosthesis converts incidental light to an electric signal which is transmitted to the neurones (bipolar cells). The subretinal prosthesis is itself sensitive to light and does not need an external device. The reference subretinal prosthesis "Retina" is manufactured by the company Retina Implant AG.

It is considered that to read a text, to move about independently and to recognise a face, minimum resolution must be more than 1,000 pixels. The subretinal prosthesis is sensitive to light with a matrix of 1,500 pixels. With an epiretinal prosthesis, resolution is only 60 pixels. However, clinical tests performed with the two types of
5 prosthesis give equivalent results, whereas there are a significantly larger number of electrodes in a subretinal prosthesis. When the number of optoelectronic components increases, the matrices become denser with smaller optoelectronic components. More precise positioning of the individual optoelectronic components becomes essential to increase the proximity between the optoelectronic component and the layer of retinal
10 ganglion cells. This allows each optoelectronic component to activate a small portion of the retina to increase visual acuity.

Moreover, known retinal prostheses are flat two-dimensional (2D) devices that are not capable of making a three-dimensional (3D) simulation, which is a significant limitation of their performance.

15 SUMMARY

More effective solutions than the current ones, without the afore-mentioned drawbacks, are therefore needed.

The solution proposed is a retinal prosthesis featuring a matrix of optoelectronic components with semiconductor optical amplifiers SOAs, which contain an active layer of
20 gallium nitride GaN with multiple quantum wells InGaN/GaAsN (gallium indium nitride/gallium arsenide nitride) or InGaN/AlGaN (gallium indium nitride/gallium aluminium nitride) on a substrate of gallium nitride GaN with p-type doping and covered with a layer of gallium nitride GaN with n-type doping.

The semiconducting material GaN has the advantage of having good chemical
25 stability and bio-compatibility. For this reason, it is possible to encapsulate materials that are not well tolerated by the human organism in this material since it creates a protective barrier.

The semiconducting material GaN also has the characteristic of being transparent in the wavelength range of visible light. In this way, the retina cells that are
30 still functional are not affected by the opacity of the retinal prosthesis. Furthermore, the

retina cells not affected are still stimulated since the retinal prosthesis does not mask the visible light penetrating the eye.

Thus the optoelectronic devices with a matrix containing optoelectronic components based on a gallium nitride GaN structure with Multi Quantum Wells (MQW) InGaN/GaAsN or InGaN/AlGaIn present the advantage of letting the light pass between two neighbouring optoelectronic components.

From one viewpoint, the substrate of gallium nitride (GaN) with p-type doping forms a column of pGaIn.

From another viewpoint, the column of p-GaIn is covered with an insulating layer of bio-compatible material chosen from carbon, diamond, titanium dioxide TiO₂, silicon SiO₂, silicon nitride Si₃N₄ or gallium nitride GaN.

From yet another viewpoint, the ratio between the height and the cross dimension of the pGaIn column is less than 20.

According to one method of construction, the optoelectronic device has a matrix of optoelectronic components that comprises semiconductor optical amplifiers SOAs of different heights.

According to another method of construction, the matrix of optoelectronic components has semiconductor optical amplifiers SOAs with vertical cavity or semiconductor optical amplifiers SOAs with horizontal cavity. When the matrix of optoelectronic components has at least one semiconductor optical amplifier SOA with vertical cavity, two distributed Bragg reflectors are placed on each side of the active GaN layer with multi quantum wells so that an optical cavity is defined.

According to yet another method of construction, the matrix of optoelectronic components is a three-dimensional (3D) matrix of semiconductor optical amplifiers SOAs with vertical cavity or semiconductor optical amplifiers SOAs with horizontal cavity.

The semiconductor optical amplifiers SOAs should be spaced at distance E such that $E^2 = \pi (350/2)^2 \times 1/n$ where n is the number of optoelectronic components in the matrix.

A transparent matrix of semiconductor optical amplifiers SOAs amplifies the blue, yellow or green light to improve the results obtained with the optogenetic technique, or with epiretinal or subretinal prostheses.

According to one method of construction, the optoelectronic component is a photodiode. The use of a transparent matrix of photodiodes with multi quantum wells InGaN/GaAsN or InGaN/AlGaN eliminates the need for the micro-camera used today with the epiretinal prosthesis.

According to another method of construction, the matrix of optoelectronic components also has vertical or horizontal photodiodes. The matrix of optoelectronic components should preferably contain at last one photodiode and at least one semiconductor optical amplifier SOA.

According to another method of construction, the optoelectronic device has a matrix of optoelectronic components that comprises vertical or horizontal photodiodes of different heights. The photodiodes and semiconductor optical amplifiers SOAs are of different heights in order to more accurately stimulate the layer of retinal ganglion cells and/or the optical nerve.

The vertical or horizontal photodiodes should be spaced at distance E such that $E^2 = \pi (350/2)^2 \times 1/n$ where n is the number of optoelectronic components in the matrix.

A retinal prosthesis, which is an epiretinal prosthesis, is also proposed.

A retinal prosthesis, which is a subretinal prosthesis, is also proposed.

A retinal prosthesis featuring both a subretinal prosthesis and an epiretinal prosthesis, is also proposed.

According to one viewpoint, an epiretinal or subretinal prosthesis features a matrix with at least one vertical photodiode.

According to a second viewpoint, an epiretinal or subretinal prosthesis features a matrix with at least one horizontal photodiode.

According to a third viewpoint, an epiretinal or subretinal prosthesis features a matrix with at least one semiconductor optical amplifier with vertical cavity.

According to a fourth viewpoint, an epiretinal or subretinal prosthesis features a matrix with at least one semiconductor optical amplifier with horizontal cavity.

According to yet another viewpoint, at the same time at least one matrix of photodiodes and at least one matrix of semiconductor optical amplifiers SOAs can be incorporated into the same epiretinal or subretinal prosthesis in order to stimulate the neurons by both injecting an electric signal and amplifying the blue, green or yellow light.

BRIEF DESCRIPTION

Other characteristics and advantages of the present invention will become apparent upon reading the following description of embodiments, naturally given by way of illustrative and non-limiting examples, and in the attached drawing in which

- figure 1 illustrates a schematic cross-sectional view of a human eye
- figure 2 illustrates a schematic cross-sectional view of the retina
- figures 3a, 3b and 3c illustrate schematically an embodiment of an optoelectronic component according to the invention
- figure 4 illustrates schematically an embodiment of an optoelectronic device with a vertical photodiode applicable to a subretinal prosthesis
- figure 5 illustrates schematically an embodiment of an optoelectronic device with a vertical photodiode applicable to an epiretinal prosthesis
- figure 6 illustrates schematically an embodiment of an optoelectronic device with a semiconductor optical amplifier with vertical cavity applicable to a subretinal prosthesis
- figure 7 illustrates schematically an embodiment of an optoelectronic device with a semiconductor optical amplifier with vertical cavity applicable to an epiretinal prosthesis
- figure 8 illustrates schematically an embodiment of an optoelectronic device with a vertical photodiode and a semiconductor optical amplifier with vertical cavity applicable to a subretinal prosthesis
- figure 9 illustrates schematically an embodiment of an optoelectronic device with a vertical photodiode and a semiconductor optical amplifier with vertical cavity applicable to an epiretinal prosthesis
- figure 10 illustrates schematically an embodiment of a matrix of optoelectronic components
- figure 11 illustrates the facet of the horizontal cavity GaN, for photodiode GaN and semiconductor optical amplifier SOA applications

- figures 12a and 12b illustrate schematically two perpendicular side views of one embodiment of an optoelectronic device consisting of a horizontal photodiode that can be applied to a sub-retinal prosthesis,
- figures 13a and 13b illustrate schematically two perpendicular side views of one embodiment of an optoelectronic device consisting of a horizontal photodiode that can be applied to an epiretinal prosthesis,
- figures 14a and 14b illustrate schematically two perpendicular side views of one embodiment of an optoelectronic device consisting of a semiconductor optical amplifier with horizontal cavity that can be applied to a sub-retinal prosthesis,
- figures 15a and 15b illustrate schematically two perpendicular side views of one embodiment of an optoelectronic device consisting of a semiconductor optical amplifier with horizontal cavity that can be applied to an epiretinal prosthesis,
- figures 16a and 16b illustrate schematically two perpendicular side views of another embodiment of an optoelectronic device consisting of a semiconductor optical amplifier with horizontal cavity that can be applied to an epiretinal prosthesis.

Directional terminology like "left" and "right", "top" and "bottom", "front" and "rear", "horizontal" and "vertical", "above" and "below", etc., is used here with reference to the orientation of the figures described. Since the components that make up the embodiments may be placed in different orientations, the directional terminology is used here only for illustrative purposes and is in no way limiting.

DETAILED DESCRIPTION

Figure 1 illustrates schematically a cross-section of a human eye **1**. It is composed of three superposed membranes **2, 3, 4** surrounding a gelatinous substance called the vitreous humour **5**.

- The anterior chamber of the eye, which receives the light, consisting of
- the iris **6** with a round opening in its centre called the pupil **7**, which allows light to pass into the eye and the size of which adapts automatically to the brightness the eye is exposed to,
 - the cornea **8**, a round, transparent, domed membrane that allows light rays to pass through,
 - the lens **9**, which focuses the image on the retina depending on the distance.

The retina **4** is the membrane that lines the inner surface of the eye's posterior chamber. The retina's nerve cells convert the light energy into electrical signals, which are transmitted to the brain by the optic nerve **10**. The blind spot **11** is the area of the eye where the fibres meet to form the optic nerve, and which contains no photosensitive cells. Nearby, the macula **12** (or yellow spot) is formed of numerous visual cells.

The most sensitive area of the retina, devoid of any blood capillaries, is called the fovea **13**. The fovea **13** is a small part of the retina found in the macula **12** (approximately 6 mm in diameter) that is sensitive to colours and is important for visual acuity. The foveola **14** (approximately 0.35 mm in diameter) is located in the middle of the fovea **13** (approximately 1.5 mm in diameter) and contains only cone cells. The fovea **13** is the part of the retina **4** with the highest visual acuity - this is where the rays of light have entered directly with the least interference, and is where the density of photoreceptor cells is at its highest. In the foveola **14**, the photoreceptor cones are longer, thinner, and more densely packed than elsewhere in the retina **4**. This ensures the foveola **14** has the highest visual acuity in the retina **4**. The photoreceptor cells convert the light energy into nervous impulses that are sent to the optic nerve.

As illustrated in the schematic cross-section view in figure 2, the retina **4** is composed of a stack of different layers arranged radially at the fovea **13**. The outer layer **20**, the layer of retinal ganglion cells (RGCs), stops the light from diffusing inside the eye. The inner layer **21**, the layer of photoreceptors (PRs), is formed of specialised nerve receptor cells **22**, with the rods and cones detecting light and the neurons processing and transmitting the visual information to the brain. The inner layer **22** is directly accessible by the foveola **14**. The middle layer **23**, or inner nuclear layer (INL), contains connecting cells such as bipolar cells.

There are several kinds of retinal prosthesis that use an optoelectronic device consisting of optoelectronic components based on a common concept as illustrated by figures 3a to 3c. This concept is based on carrying out one or more epitaxies on an intrinsic active GaN layer **30** with multiple quantum wells for InGaN/GaAsN (indium gallium nitride / arsenic gallium nitride) or InGaN/AlGaN (indium gallium nitride / aluminium gallium nitride) on a substrate **31** of p-type doped gallium nitride GaN. An intrinsic material is a semiconductive material that is not doped and/or has no impurities. Epitaxy is the crystalline growth of a material, generally carried out on the same material respecting the crystals' meshing and orientation. At the top of each active GaN layer **30**,

a layer of n-type doped GaN gallium nitride layer **32** is carried out to complete the epitaxy.

The process applied to the rear surface **33** of the p-GaN substrate **31**, wherein the p-GaN substrate **31** is thinned and polished to the desired height, results in p-GaN columns **34**. The p-GaN columns **33** are obtained by selective etching of the p-GaN substrate layer **31**, for example with a chloride inductively coupled plasma ICP.

The p-GaN column **34** must be long enough to stimulate the cells of the retina. The ratio between the height and transverse measurement (width or diameter) of the p-GaN column **34** should preferably be less than 20, to prevent the column from breaking. The p-GaN columns **34** may be different heights in order to stimulate different layers of the retina. The different heights are achieved through selective etching of the p-GaN substrate **31** for example, by starting from the rear surface. The p-GaN column **34** may take the shape of a rod with parallel edges (figure 3a), a truncated pyramid (figure 3b), or a thin rod on top of a wider base (figure 3c). In the remainder of this description, we shall consider a thin rod on top of a wider base, as shown in figure 3c.

Several optoelectronic components with a similar structure consisting of multiple quantum wells can be created using selective area growth (SAG) technology, in order to amplify or detect several wavelengths (blue, green, yellow). The various optoelectronic components found on the same matrix are electrically separated by an area of implanted GaN or semi-isolating GaN, so that the optoelectronic components are isolated from each other and the matrix remains transparent.

Figure 4 illustrates a schematic representation of an optoelectronic device embodiment, composed of at least one GaN-based vertical photodiode and intended for use in a sub-retinal prosthesis.

An absorbent active GaN layer **40** with multiple InGaN/GaAsN or InGaN/AlGaIn quantum wells is made by epitaxy on a substrate **41** of p-type doped gallium nitride GaN. A layer **42** of n-type doped gallium nitride GaN is laid on top of the absorbent GaN layer **40**. By thinning and polishing the p-GaN substrate **41**, a p-GaN column **43** is obtained at the desired height. The p-GaN column **43** is coated with an isolating layer **44** of dielectric or semi-isolating material. Furthermore, the material composing the isolating layer **44** must offer a good level of biocompatibility, such as carbon, diamond, titanium

dioxide, common dielectric materials (silica, silicon nitride, etc.) or semi-isolating GaN material. The isolation is completed by implanting semi-isolating GaN **45** to separate the optoelectronic components from each other, in order to polarise the optoelectronic components in a matrix independently.

5 A metal contact **46** is placed on the front surface of the n-type doped gallium nitride GaN layer **42**. The metal contact **46** on the front surface of the n-GaN layer **42** polarises the retinal prosthesis. Another metal contact **47** is placed at the end of the p-GaN column **43** corresponding with the area of the retina **48** that is stimulated. The metal contacts **46** and **47** are connected by an electrochemical generator **49** (battery or
10 accumulator), which establishes a voltage between them. Because the light **L** must pass through the p-GaN column **43** to reach the absorbent active GaN layer **40**, the metal contact **47** must not cover the entire upper surface of the p-GaN column **43**. A photocurrent appears, which will stimulate the retina's various layers.

 The embodiment schematically illustrated in figure 5 shows an optoelectronic
15 device consisting of at least one GaN-based vertical photodiode that is designed for use with an epiretinal prosthesis.

 An absorbent active GaN layer **50** with multiple InGa_N/GaAsN or InGa_N/AlGa_N quantum wells is made by epitaxy on a substrate **51** of p-type doped gallium nitride GaN. A layer **52** of n-type doped gallium nitride GaN is laid on top of the absorbent GaN
20 layer **50**. By thinning and polishing the p-GaN substrate **51**, a p-GaN column **53** is obtained at the desired height. The p-GaN column **53** is coated with an isolating layer **54** of dielectric or semi-isolating material. Isolation is completed by implanting semi-isolating GaN **55**. Each photodiode in a matrix may be independently polarised from its neighbour in this way, depending on the medical requirement. A metal contact **56** is placed on the
25 front surface of the n-GaN layer **52**, and another metal contact **57** is placed at the end of the p-GaN column **53** that corresponds to the area of the retina **58** to be stimulated. Because the light **L** must pass through the nGa_N column **52** to reach the absorbent active GaN layer **50**, the metal contact **56** must not cover the entire front surface of the n-GaN column **52**. A photocurrent appears, which will stimulate the retina's various
30 layers. However, the metal contact **57** may cover the entire surface at the end of the pGa_N column **53** because the induced photocurrent is enough to stimulate the different layers of the retina. Indeed, there is no need to transmit the light outside of the epiretinal area where there are no photoreceptor cells.

Replacing the retina with matrices containing thousands, if not millions, of optoelectronic components based on semiconductors, like these photodiodes, will make it possible to convert the light into an electrical signal, which will then be transmitted to the visual fibres that are still functioning.

5 We will now consider figure 6, which illustrates a schematic view of an optoelectronic device embodiment, composed of at least one GaN-based semiconductor optical amplifier with vertical cavity and intended for use in a sub-retinal prosthesis.

Remember that an optical amplifier is a device that amplifies an optical signal directly, without the need to convert it into an electrical signal beforehand. An optical
10 amplifier is different from a laser in that it has no optical cavity, or there is no retroaction produced from the cavity. The semiconductor optical amplifiers SOAs are optical amplifiers that use semiconductive material to provide the gain medium. These semiconductor optical amplifiers SOAs contain anti-reflective parts at its end surfaces, which results in energy loss from the cavity that is above the gain, thus preventing the
15 optical amplifier from working like a laser.

An amplifying active GaN layer **60** with multiple InGaN/GaAsN or InGaN/AlGaIn quantum wells is made by epitaxy on a substrate **61** of p-type doped gallium nitride GaN. A layer **62** of n-type doped gallium nitride GaN is laid on top of the amplifying GaN layer **60**. Two distributed Bragg reflectors DBRs **63** are placed on either side of the
20 amplifying GaN layer **60**.

By thinning and polishing the p-GaN substrate **61**, a p-GaN column **64** is obtained at the desired height. The p-GaN column **64** is coated with an isolating layer **65** of dielectric or semi-isolating material.

A metal contact **66** is placed on the front surface of the n-GaN layer **62**, and
25 another metal contact **67** is placed at the end of the p-GaN column **64** that corresponds to the area of the retina **68** to be stimulated. Since on the one hand the incident light **L** must be able to penetrate the p-GaN substrate **61** to reach the amplifying GaN layer **60**, and on the other hand the amplified light **AL** must be able to reach the area that requires stimulation **68**, the metal contact **67** must not cover the entire surface at the end of
30 the p-GaN column **64**.

The distributed Bragg reflectors DBRs **63** define an optical cavity in which blue light is amplified. All of the blue light is reflected on the mirror created by the metal contact **66** covering the front surface of the n-GaN layer **62**.

After carrying out an optogenetic operation, the retinal cells will be selectively
5 stimulated by the amplified blue light **AL**. An anti-reflective coating **69** is necessary on the top end of the pGaN column **64** in order to prevent parasite reflections and improve the quality of optical transmission.

Figure 7 illustrates a schematic view of an optoelectronic device embodiment, composed of at least one GaN-based semiconductor optical amplifier with vertical cavity
10 and intended for use in an epiretinal prosthesis.

An amplifying active GaN layer **70** with multiple InGa_N/GaAs_N or InGa_N/AlGa_N quantum wells is made by epitaxy on a substrate **71** of p-type doped gallium nitride GaN. A layer **72** of n-type doped gallium nitride GaN is laid on top of the amplifying GaN layer **70**. Two distributed Bragg reflectors DBRs **73** are placed on either side of the
15 amplifying GaN layer **70**.

By thinning and polishing the p-GaN substrate **71**, a column of p-GaN of the desired height **74** is produced. The p-GaN layer **74** is covered with an insulating layer **75** of dielectric or semi-insulating material.

A metal contact **76** is placed on the front face of the n-GaN layer **72** and another
20 metal contact **77** is placed at the end of the p-GaN column **74** corresponding to the area of retina **78** to be stimulated. Because the incident blue light **L** has to cross the n-GaN layer **72** to reach the GaN amplifying layer **70**, the metal contact **76** must not cover the entire surface of the front face of the n-GaN layer **72**. Once the blue light **LA** has been amplified it has to leave the column of p-GaN **74** to stimulate the neighbouring layers 78
25 of the retina, where the optogenetic therapy has been active, and the metal contact **77** must therefore not cover the entire surface of the end of the column of p-GaN **74**.

The blue light is amplified in the optical cavity defined by the two distributed Bragg reflectors DBRs **73**, positioned either side of the GaN amplification layer **70**. After an optogenetic operation, the retina cells will be selectively stimulated by this amplified
30 blue light **LA**. An anti-reflection coating **79** is required at the upper end of the p-GaN

column **74** to prevent parasitic reflections, and to improve the optical transmission quality.

It may be advantageous to combine an optoelectronic device intended as a subretinal prosthesis with an optoelectronic device intended as an epiretinal prosthesis, whether or not they have the same operational mode. For example, a subretinal prosthesis containing optical amplifiers can be combined with an epiretinal prosthesis containing photodiodes, in particular in cases where optogenetic therapy proves more effective for cells close to the layer of ganglion cells than for photoreceptive cells such as cones. Or inversely, an epiretinal prosthesis containing optical amplifiers can be combined with a subretinal prosthesis containing photodiodes. It is also possible to combine photodiodes and optical amplifiers in a single epiretinal or subretinal prosthesis. This can be achieved by the use of vias (metallised holes) to produce direct and indirect polarisation of the optoelectronic components.

In the embodiment illustrated schematically in figure 8, an optoelectronic device containing at least one GaN-based photodiode and at least one vertical cavity GaN-based semiconductor optical amplifier combined, is intended for use in a subretinal prosthesis.

Photodiode **80**, analogous to that in figure 4, contains an active absorbent GaN layer **81** with multiple InGaN/GaAsN or InGaN/AlGaIn quantum wells deposited on a p-GaN substrate **82** and surmounted by an n-GaN layer **83** which is cut to form a column of p-GaN **84**. A metal contact **85** is deposited on the n-GaN layer **83** and another metal contact **86** partially covers the upper end of the p-GaN column **84** corresponding to the area of retina **87** to be stimulated.

The vertical cavity semiconductor optical amplifier **100** contains a GaN amplifying layer **101** with multiple InGaN/GaAsN or InGaN/AlGaIn quantum wells, deposited on a p-GaN substrate **102** and surmounted by a n-GaN layer **103** which is cut to form a column of p-GaN **104**. Two distributed Bragg reflectors DBRs **105** are placed either side of the GaN amplifying layer **101**. A metal contact **106** is deposited on the n-GaN layer **103** and another metal contact **107** partially covers the upper end of the p-GaN column **102** corresponding to the area of retina **108** to be stimulated.

The multiple quantum well structure of the photodiode and the multiple quantum well structure of the vertical cavity semiconductor amplifier can be adapted with distributed Bragg reflectors, by using butt-joint epitaxy.

We now consider figure 9, schematically illustrating an embodiment for an optoelectronic device containing at least one GaN-based photodiode and at least one vertical cavity GaN-based semiconductor optical amplifier combined, intended for use in an epiretinal prosthesis.

Photodiode **90**, analogous to that in figure 5, contains an active absorbent GaN layer **91** with multiple InGaN/GaAsN or InGaN/AlGaIn quantum wells deposited on a p-GaN substrate **92** and surmounted by an n-GaN layer **93** which is cut to form a column of p-GaN **94**. A metal contact **95** is deposited on the n-GaN layer **93** and another metal contact **96** partially covers the upper end of the p-GaN column **94** corresponding to the area of retina **97** to be stimulated.

The vertical cavity semiconductor optical amplifier **110** contains a GaN amplifying layer **111** with multiple InGaN/GaAsN or InGaN/AlGaIn quantum wells, deposited on a p-GaN substrate **112** and surmounted by an n-GaN layer **113** which is cut to form a column of p-GaN **114**. Two distributed Bragg reflectors DBRs **115** are placed either side of the GaN amplifying layer **111**. A metal contact **116** is deposited on the n-GaN layer **113** and another metal contact **117** partially covers the upper end of the p-GaN column **112** corresponding to the area of retina **118** to be stimulated.

It thus becomes possible to replace the retina by a prosthesis consisting of an optoelectronic device containing thousands or even millions of optoelectronic components in a matrix, as illustrated in figure 10.

An important parameter is the distance between two optoelectronic components in a matrix. There must be enough free space between the optoelectronic components for the active cells in the internal nuclear layer INL or the ganglion cell layer GCL to function normally. It may in particular be interesting to enable organic tissues to be introduced between the individual optoelectronic components. But there must also be a sufficient number of optoelectronic components (photodiodes or optical amplifiers) to allow the patient good image definition.

The foveola has a diameter of approximately 0.35 mm. The spacing **E** between two adjacent devices is given by the following relation, where *n* is the number of optoelectronic components in the matrix:

$$E^2 (\mu\text{m}) = \pi (350/2)^2 \times 1/n$$

5 In the case of a matrix with 2000 optoelectronic components, the spacing **D** is about 48 μm . The height **H** of the p-GaN column must be less than 480 μm , given that the thickness of the retina is generally less than 0.5 mm. In an optoelectronic device containing optoelectronic components in which the p-GaN column has a transverse dimension **D** (width or diameter) of about 24 μm , there remains 24 μm available to allow,
10 for example, for metal contacts and electrical connections.

Figure 11 schematically illustrates the facet of the horizontal GaN cavity, for GaN photodiode and semiconductor optical amplifier SOA applications. The facet is bevelled at an angle α . To obtain total reflection on the guide layers of the MQW-based optical guide OG with an overall optical index *n*₁ and the confinement layers with an
15 overall optical index *n*₂, the angle θ must be greater than the Brewster angle θ_{Brewster} and defined by the following inequalities:

$$\begin{aligned} n_1 &> n_2 \\ \theta &> \theta_{\text{Brewster}} \\ \alpha &> \theta_{\text{Brewster}} \\ \beta &< \pi/2 - \theta_{\text{Brewster}} \\ \theta_{\text{Brewster}} &= \arcsin(n_2/n_1) \end{aligned}$$

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Figures 12a and 12b schematically illustrate an embodiment of an optoelectronic device, containing at least one GaN-based horizontal photodiode, intended for use in a subretinal prosthesis. Figure 12a is a side view of the device in
25 which light is propagated in the plane of the figure, and figure 12b is another side view of the device perpendicular to figure 12a.

An active absorbent GaN amplifying layer **120** with multiple InGaN/GaAsN or InGaN/AlGaIn quantum wells is made by epitaxy on a p-doped gallium nitride GaN substrate **121**. A layer **122** of n-doped gallium nitride GaN is deposited above the GaN absorbent layer **120**. By selective etching of the p-GaN substrate **121** using an
30 inductively coupled plasma ICP, a column of p-GaN **123** is formed up to the desired height, sufficient to allow stimulation of the retinal cells. The p-GaN layer **123** is covered with an insulating layer **124** of dielectric or semi-insulating material. Furthermore, the

material composing the insulating layer **124** must have good biocompatibility, such as carbon, diamond, titanium dioxide, common dielectric materials (silica, silicon nitride, etc.) or the semi-insulating material GaN. The insulation is completed by implanting semi-insulating GaN **125** to separate the optoelectronic components from each other, to
5 allow each of the optoelectronic components in the matrix to be polarised independently.

On the front face of the n-doped gallium nitride GaN layer **122**, a metal layer **126** is deposited. The metal contact **126** on the front face of the n-GaN layer **122** allows the retinal prosthesis to be polarised. Another metal contact **127** is placed at the upper end of the p-GaN column **123** corresponding to the area of the retina **128** that is
10 stimulated. The metal contacts **126** and **127** are connected by an electrochemical generator **129** (primary or rechargeable battery) which applies a voltage between them. Because the light **L** has to cross the p-GaN column **123** to reach the absorbent GaN amplifying layer **120**, the metal contact **127** must not cover the entire surface of the front face of the p-GaN column **123**. There appears a photocurrent which will stimulate the
15 various layers of the retina.

In the embodiment illustrated in figures 13a and 13b, an optoelectronic device containing at least one GaN-based horizontal photodiode intended for use in an epiretinal prosthesis is illustrated. Figure 13a is a side view of the device in which light is propagated in the plane of the figure, and figure 13b is another side view of the device
20 perpendicular to figure 13a.

An active absorbent GaN amplifying layer **130** with multiple InGaN/GaAsN or InGaN/AlGaIn quantum wells is made by epitaxy on a p-doped gallium nitride GaN substrate **131**. A layer **132** of n-doped gallium nitride GaN is deposited above the GaN absorbent layer **130**. From the p-GaN substrate **131**, a column of p-GaN of the desired
25 height **133** is produced. The p-GaN layer **133** is covered with an insulating layer **134** of dielectric or semi-insulating material. The insulation is completed by implanting semi-insulating GaN **135**. Each photodiode in a matrix can thus be polarised independently from its neighbour according to medical requirements. A metal contact **136** is placed on the front face of the n-GaN layer **132** and another metal
30 contact **137** is placed at the end of the p-GaN column **133** corresponding to the area of retina **138** to be stimulated.

The light must enter through the bevelled edge of the optical guide OG. The bevelled edge inclined at an angle α has a TiO_2 and SiO_2 -based anti-reflection coating that has been deposited to ensure good optical transmission between the exterior of the device and the guide layers. A photoelectric current appears, stimulating the various layers of the retina.

Figures 14a and 14b schematically illustrate an embodiment of an optoelectronic device, containing at least one horizontal cavity GaN-based semiconductor optical amplifier, intended for use in a subretinal prosthesis. Figure 14a is a side view of the device in which light is propagated in the plane of the figure, and figure 14b is another side view of the device perpendicular to figure 14a.

An active GaN amplifying layer **140** with multiple InGaN/GaAsN or InGaN/AlGaIn quantum wells is made by epitaxy on a p-doped gallium nitride GaN substrate **141**. A layer **142** of n-doped gallium nitride GaN is deposited above the GaN amplifying layer **140**. The p-GaN layer **141** is covered with an insulating layer **143** of dielectric or semi-insulating material.

A metal contact **144** is placed on the front face of the n-GaN layer **142** and another metal contact **145** is placed at the end of the p-GaN layer **141** corresponding to the area of retina **146** to be stimulated. Because part of the incident light **L** has to be able to cross the p-GaN substrate **141** to reach the GaN amplifying layer **140**, and another part of the amplified light **LA** has to be able to reach the area to be stimulated **146**, the metal contact **145** must not cover the entire surface of the end of the p-GaN layer **141**. After an optogenetic operation, the retina cells will be selectively stimulated by the amplified blue light **LA**.

Figures 15a and 15b schematically illustrate an embodiment of an optoelectronic device, containing at least one horizontal cavity GaN-based semiconductor optical amplifier, intended for use in an epiretinal prosthesis. Figure 15a is a side view of the device in which light is propagated in the plane of the figure, and figure 15b is another side view of the device perpendicular to figure 15a.

An active GaN amplifying layer **150** with multiple InGaN/GaAsN or InGaN/AlGaIn quantum wells is made by epitaxy on a p-doped gallium nitride GaN substrate **151**. A layer **152** of n-doped gallium nitride GaN is deposited above the GaN

amplifying layer **150**. The p-GaN layer **151** is covered with an insulating layer **153** of dielectric or semi-insulating material.

A metal contact **154** is placed on the front face of the n-GaN layer **152** and another metal contact **155** is placed at the end of the p-GaN layer **151** corresponding to the area of retina **156** to be stimulated. The incident blue light **L** must reach the GaN amplifying layer **150**, and once the blue light **LA** is amplified it will stimulate the layers close to the retina. After an optogenetic operation, the retina cells will be selectively stimulated by this amplified blue light **LA**.

Figures 16a and 16b schematically illustrate another embodiment of an optoelectronic device, containing at least one semiconductor optical amplifier based on horizontal cavity GaN, intended for use in an epiretinal prosthesis. Figure 16a is a side view of the device in which light is propagated in the plane of the figure, and figure 16b is another side view of the device perpendicular to the plane of figure 16a.

In this other version, the p-doped gallium nitride GaN substrate **160** is etched to allow light **L** to pass. It is also useful to first of all etch the substrate and then the edge of the semiconductor optical amplifier SOA to create a bevelled edge. The blue light **LA** is amplified in the optical cavity defined by the two bevelled edges. After the optogenetic treatment, the retina cells are selectively stimulated by this amplified blue light **LA**. One of the bevelled edges **161** is the input of the signal which is to be amplified. The second **162** is the output of the amplified blue light **LA**. The bevelled edges are inclined at an angle α that is below the limit of the Brewster angle. An anti-reflection coating based on layers of TiO_2 and SiO_2 has been deposited to ensure good optical transmission between the exterior of the device and the guiding layers.

It may be interesting to mix a subretinal prosthesis with an epiretinal prosthesis having the same or a different operating mode. It is also possible to mix the two operating modes, subretinal and epiretinal, in a single retinal prosthesis by the use of metallised holes or vias, to cause the direct and indirect polarisation of the optoelectronic components. It is possible to adapt the structure of multi-quantum wells of the photodiode and the multi-quantum wells of the horizontal cavity of the semiconductor optical amplifier SOA, by the use of butt-joint epitaxy.

Naturally, this invention is not limited to the described embodiments, and is open to many variants accessible to the person skilled in the art in the field without departing from the spirit of the invention. In particular, the composition of the active layer could be modified for any III-V semiconductor tuned to the GaN and active in the visible domain, i.e. with a photoluminescence peak in the blue-green-yellow zone.

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CLAIMS

1. Retinal prosthesis containing a matrix of optoelectronic components including semiconductor optical amplifiers SOAs, the said semiconductor optical amplifiers SOAs containing an active layer of gallium nitride GaN with multiple InGaN/GaAsN (indium-gallium nitride / arsenic-gallium nitride) or InGaN/AlGaN (indium-gallium nitride / aluminium-gallium nitride) quantum wells on a substrate of p-doped gallium nitride GaN and covered with a layer of n-doped gallium nitride GaN.
2. Retinal prosthesis according to claim 1 in which the p-doped gallium nitride GaN substrate forms a column of p-GaN.
3. Retinal prosthesis according to claim 2, in which the column of p-GaN is covered with an insulating layer of biocompatible material chosen from carbon, diamond, titanium dioxide, silica, silicon nitride or gallium nitride.
4. Retinal prosthesis according to claims 2 and 3 in which the ratio of the height to the transverse dimension of the p-GaN column is less than 20.
5. Retinal prosthesis according to any preceding claim in which the matrix of optoelectronic components contains semiconductor optical amplifiers SOAs with different heights.
6. Retinal prosthesis according to any preceding claim in which the matrix of optoelectronic components contains semiconductor optical amplifiers SOAs spaced at a distance E such that $E^2 = \pi (350/2)^2 \times 1/n$ where n is the number of optoelectronic components in the matrix.
7. Retinal prosthesis according to any preceding claim in which the matrix of optoelectronic components contains vertical cavity semiconductor optical amplifiers SOAs or horizontal cavity semiconductor optical amplifiers SOAs.
8. Retinal prosthesis according to claim 7 in which the matrix of optoelectronic components contains at least one vertical cavity semiconductor optical amplifier in which two distributed Bragg reflectors are placed respectively on either side of

the active GaN layer with multiple quantum wells in such a way as to define an optical cavity.

- 5 9. Retinal prosthesis according to claim 7 in which the matrix of optoelectronic components is a three-dimensional matrix of vertical cavity semiconductor optical amplifiers or horizontal cavity semiconductor optical amplifiers.
10. Retinal prosthesis according to any preceding claim, in which the matrix of optoelectronic components further contains vertical and horizontal photodiodes.
11. Retinal prosthesis according to claim 10 in which the matrix of optoelectronic components contains vertical or horizontal photodiodes with different heights.
- 10 12. Retinal prosthesis according to one of claims 10 and 11, in which the matrix of optoelectronic components contains vertical or horizontal photodiodes spaced at a distance E such that $E^2 = \pi (350/2)^2 \times 1/n$ where n is the number of optoelectronic components in the matrix.
- 15 13. Retinal prosthesis according to one of claims 1 to 12 which is an epiretinal prosthesis.
14. Retinal prosthesis according to one of claims 1 to 12 which is a subretinal prosthesis.
15. Retinal prosthesis according to one of claims 13 and 14 simultaneously containing a subretinal and epiretinal prosthesis.

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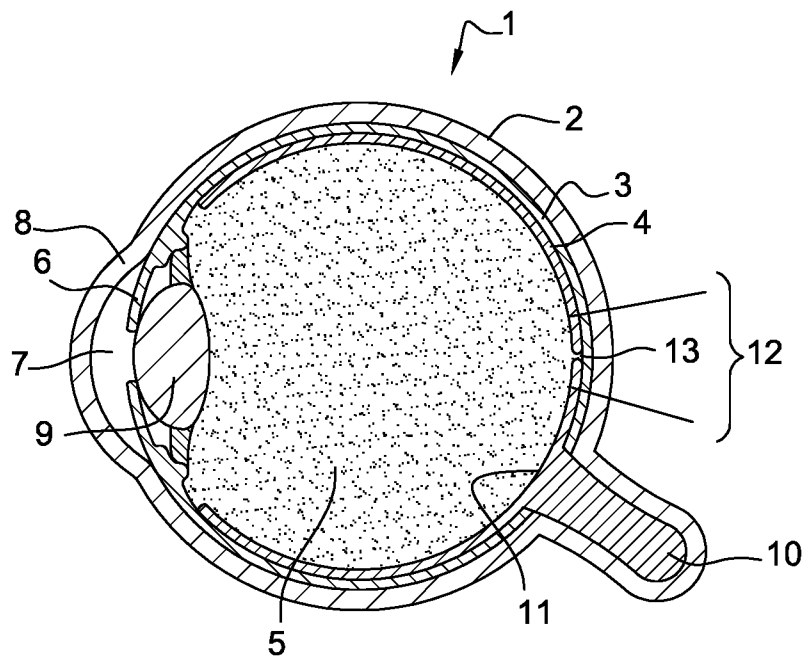


Fig. 1

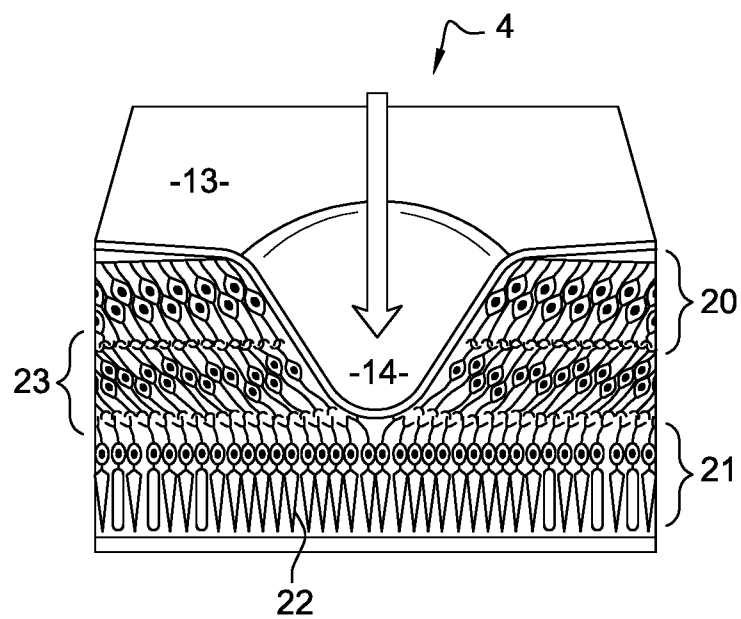


Fig. 2

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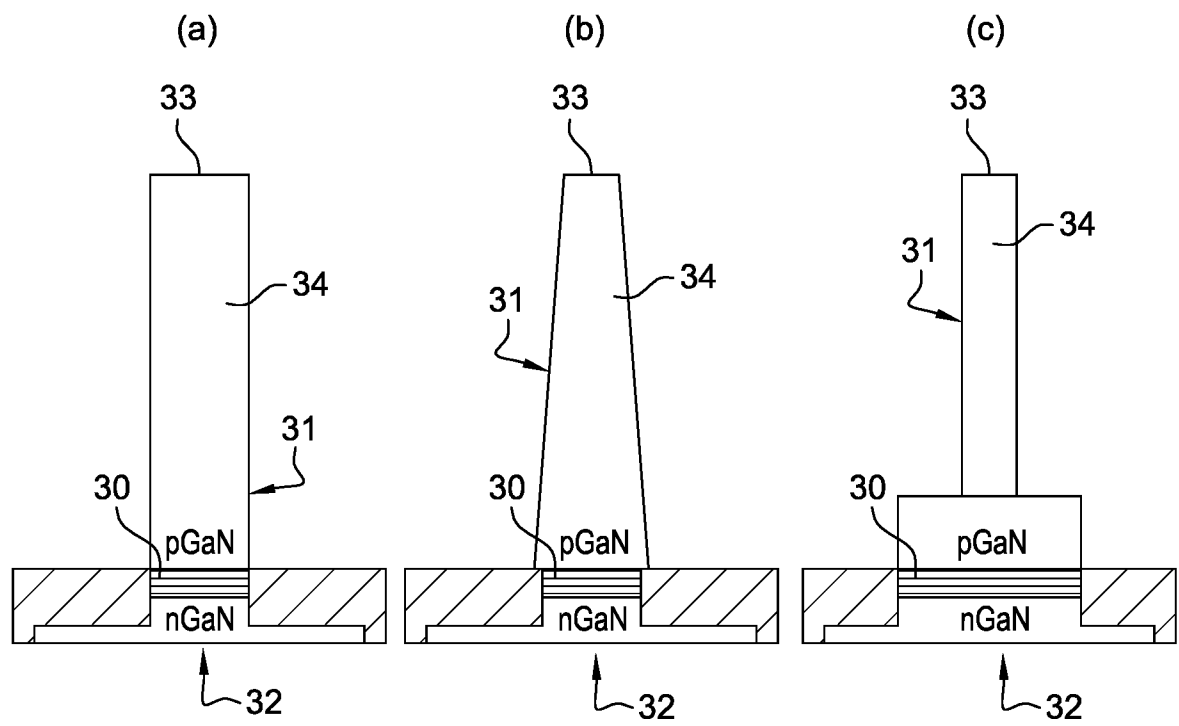
**Fig. 3**

Fig. 4

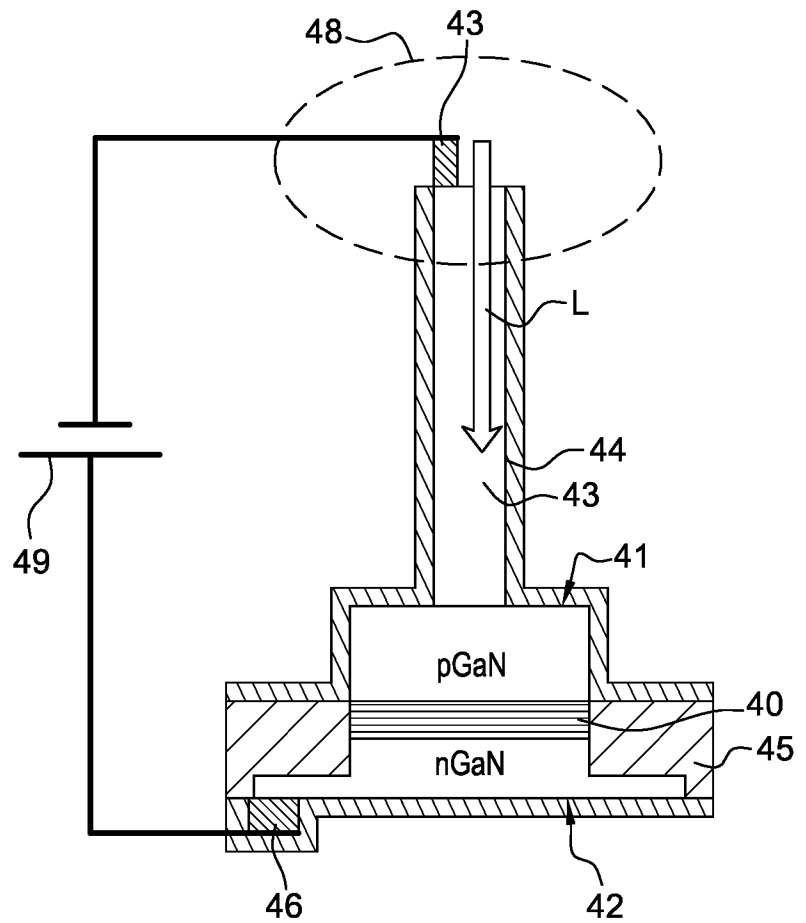


Fig. 5

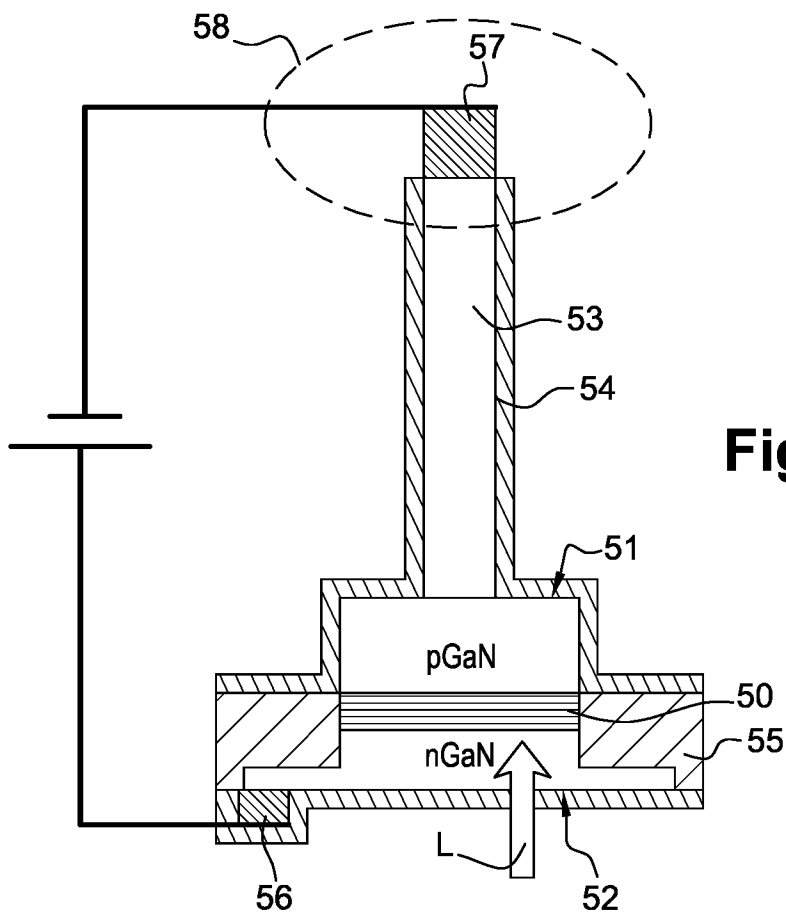


Fig. 6

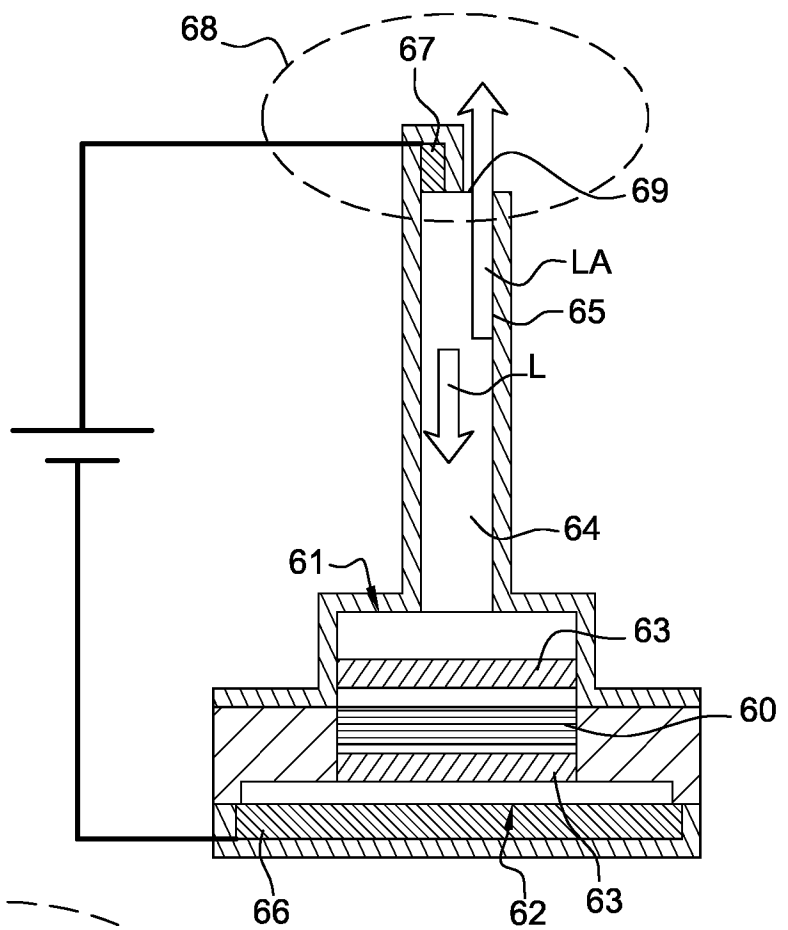
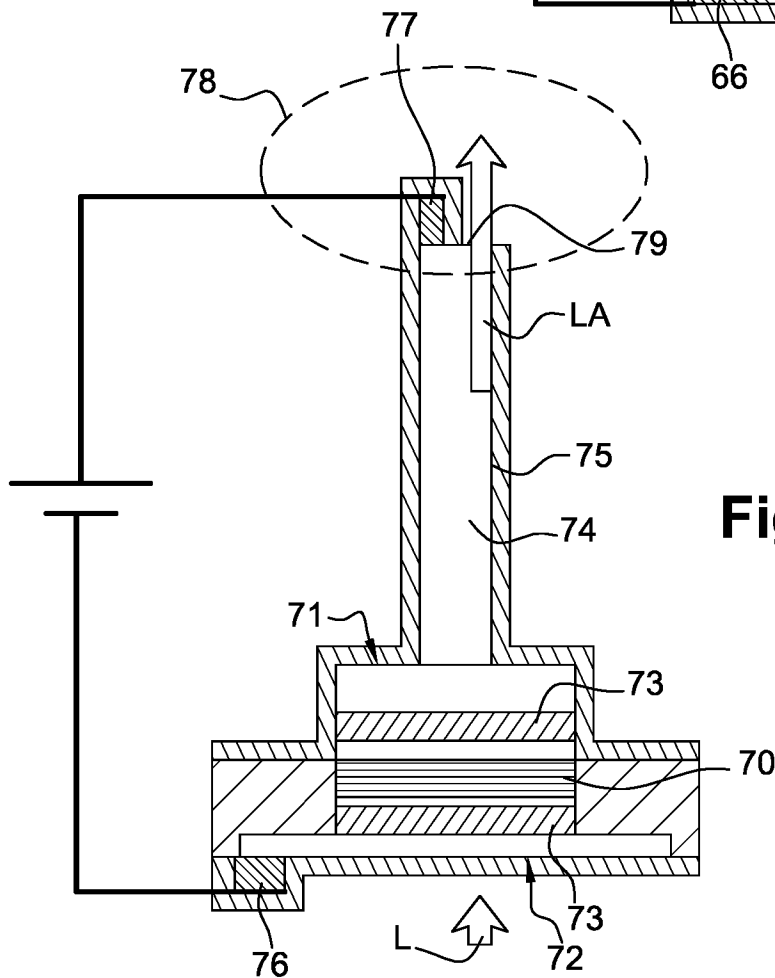
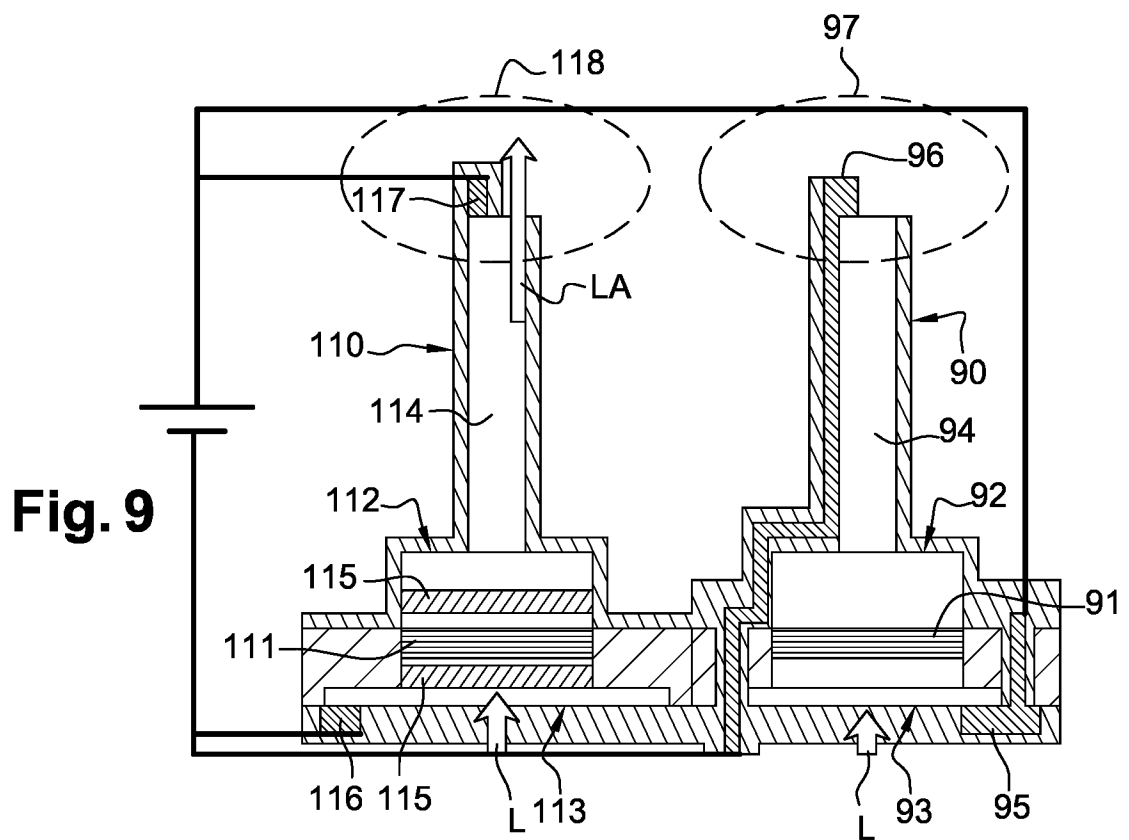
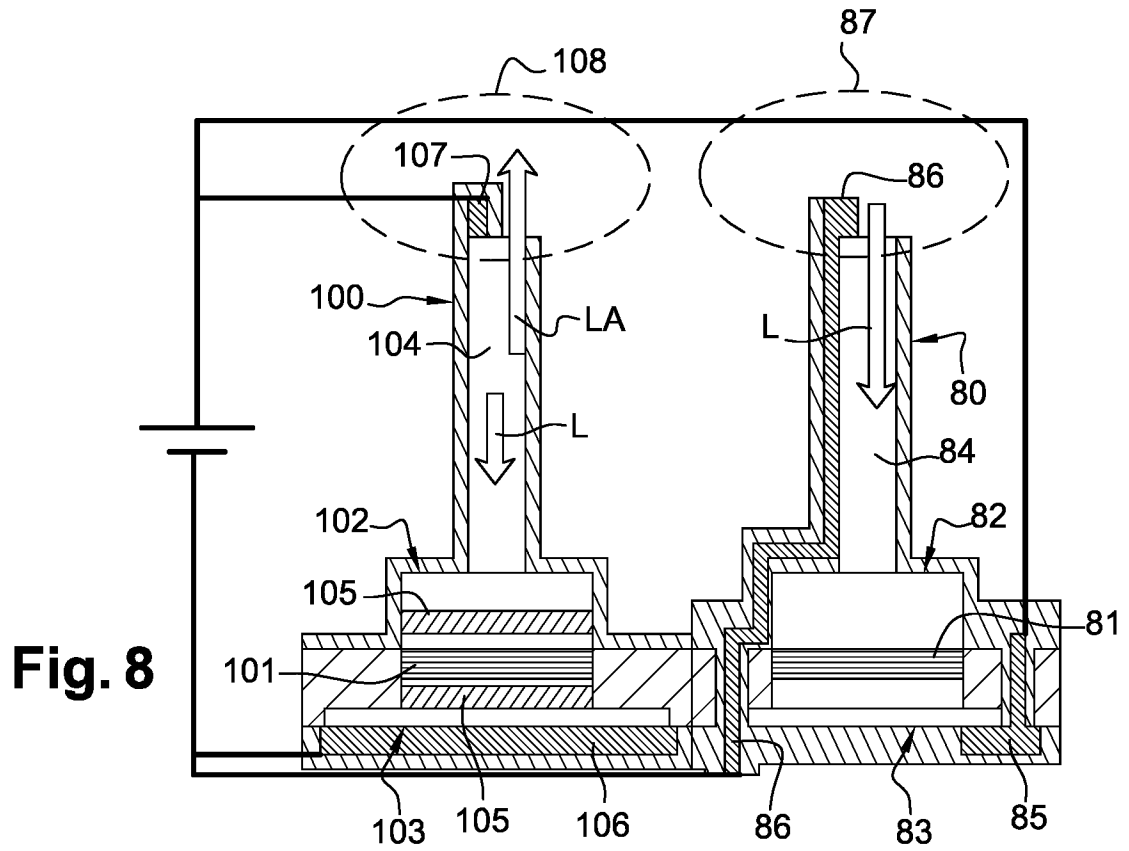
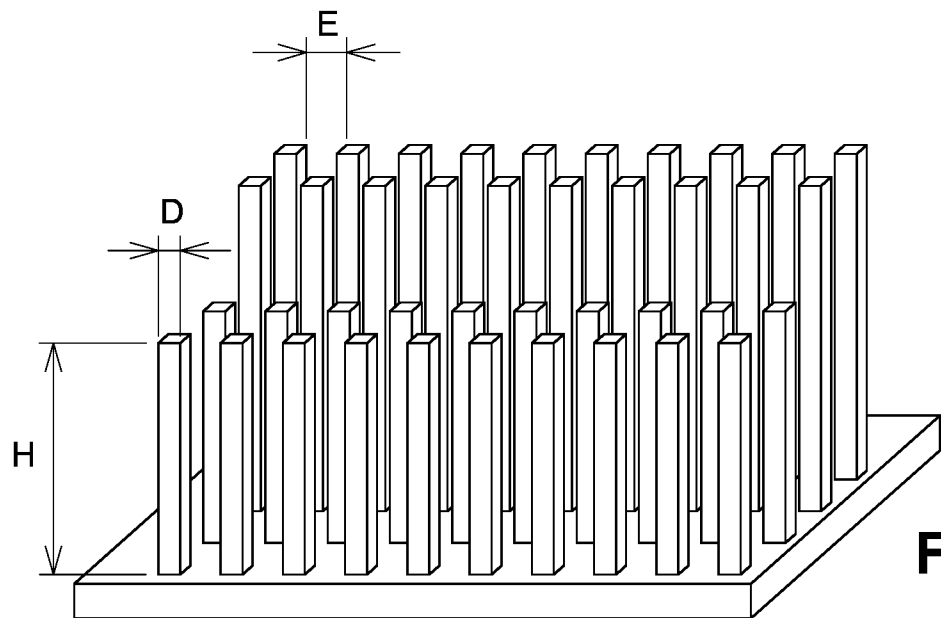
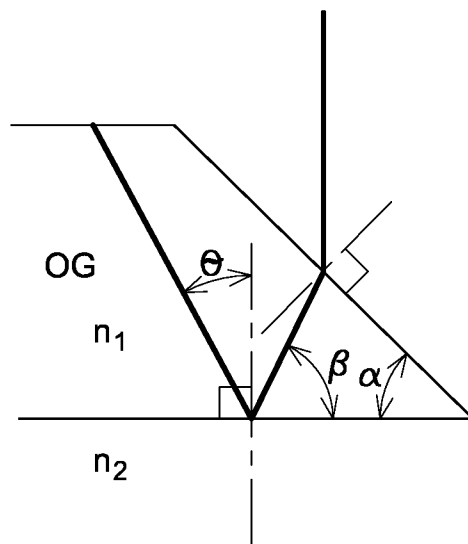


Fig. 7





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**Fig. 10****Fig. 11**

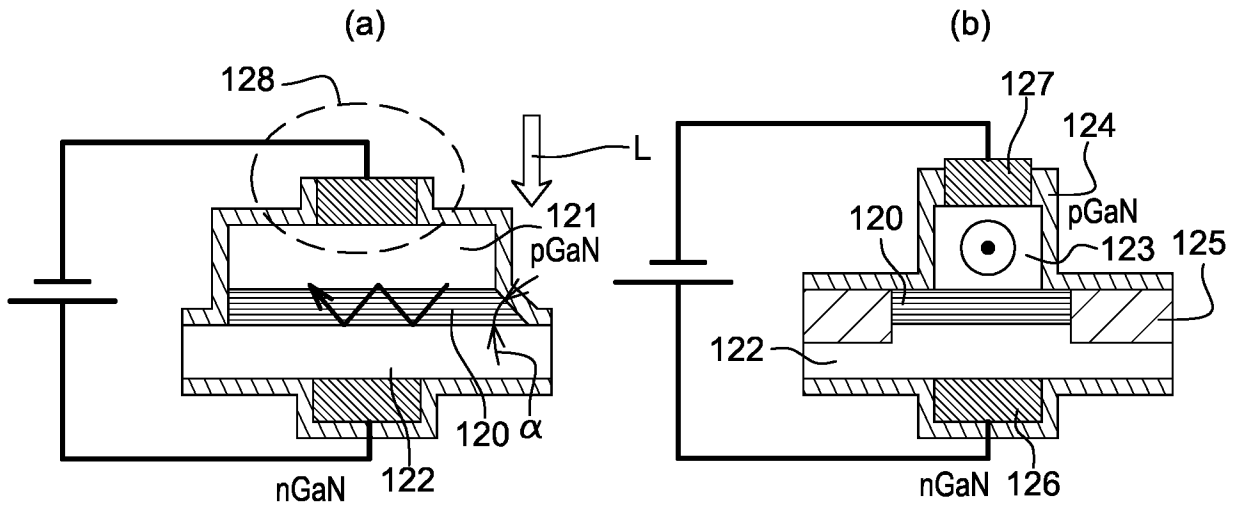


Fig. 12

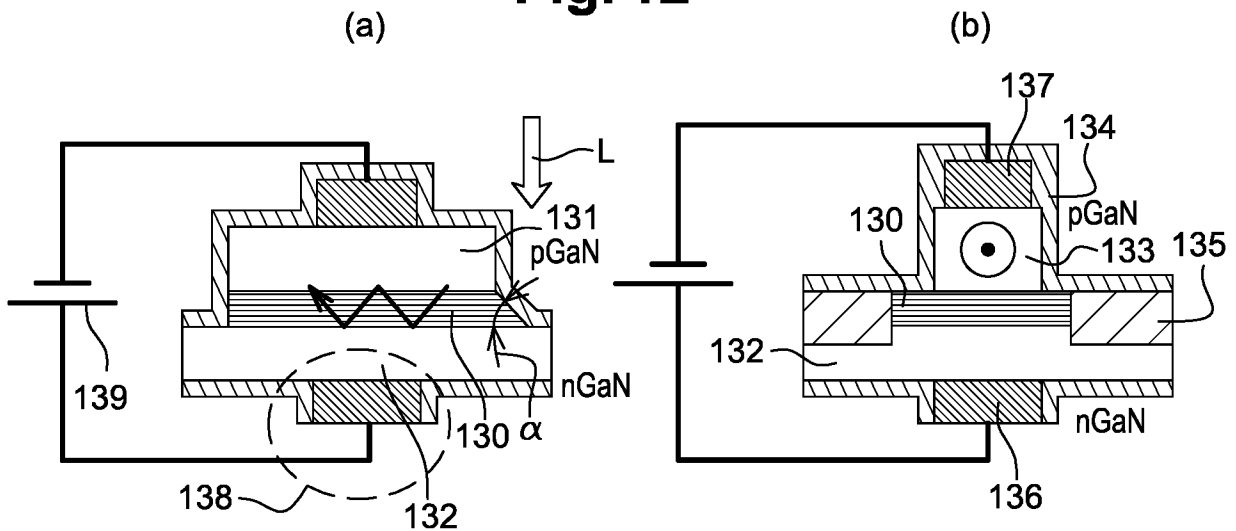


Fig. 13

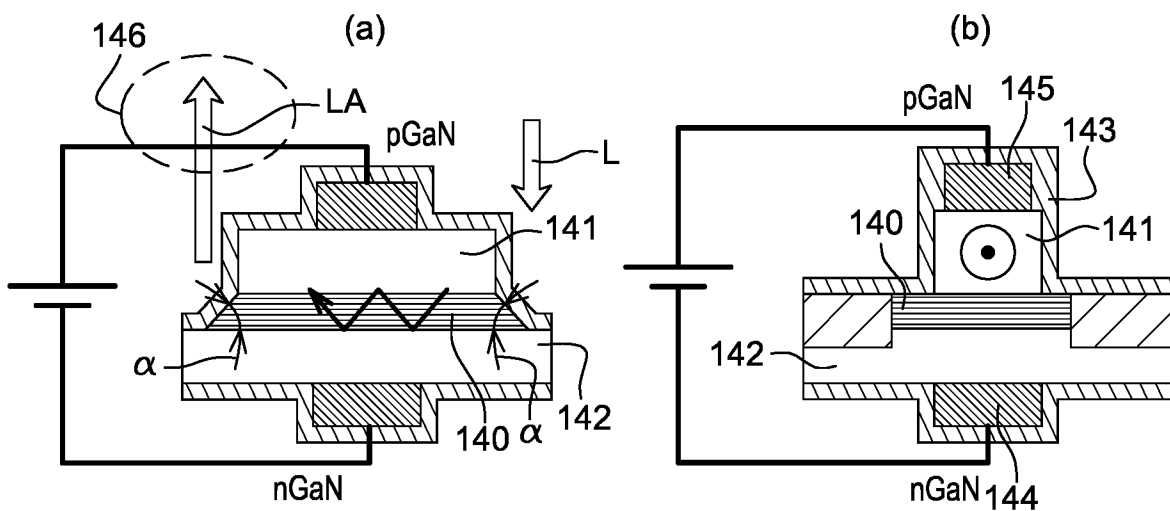
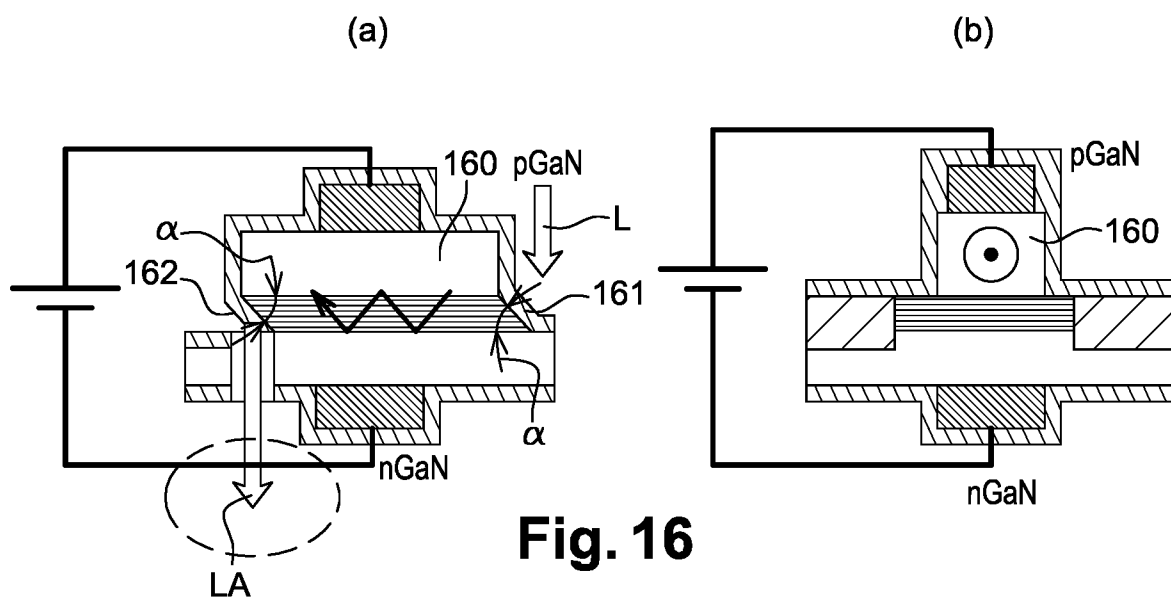
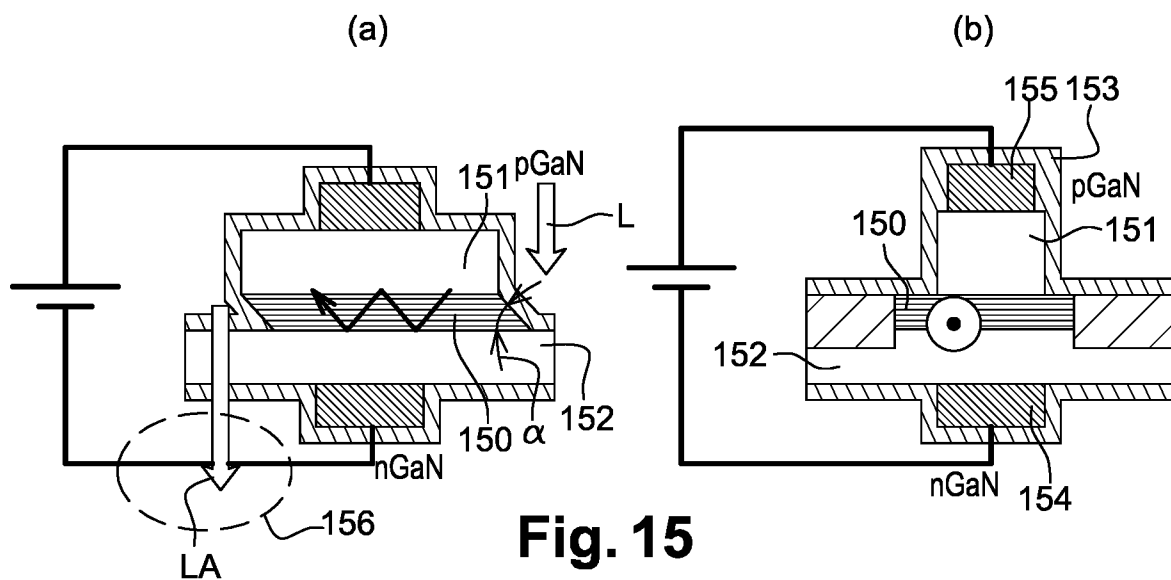


Fig. 14



INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/053993

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01L31/0304 H01L31/0352 H01L27/146 H01L31/105 A61F2/14
A61N1/05 H01S5/50

ADD.

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)

H01L A61F A61N 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 practicable, search terms used)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

18 May 2016

Date of mailing of the international search report

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Authorized officer

Sagol, Bülent Erol

INTERNATIONAL SEARCH REPORT

International application No

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