Abstract: The present invention relates to an Al In Ga N-based superluminescent diode, comprising a semiconductor substrate (1), a lower cladding layer (2) with n-type electric conductivity, a lower light-guiding layer (3) with n-type electric conductivity, a light emitting layer (4), an electron blocking layer (5) with p-type electric conductivity, an upper light-guiding layer (6), an upper cladding layer (7) with p-type electric conductivity, a subcontact layer (8) doped with acceptors in concentration higher than 1020 cm-3, and an antireflective layer deposited on the output facet (12) of the waveguide, wherein the antireflective layer contains dielectric nanoparticles (14) whose largest geometrical measurement is smaller than the wavelength of the light emitted by the diode.
AlInGaN-based superluminescent diode

The present invention relates to AlInGaN-based superluminescent diode applicable in optoelectronics, photonics, and fiber-optic systems, particularly as visible radiation source.

Superluminescent diodes are usually manufactured as devices with separate confinement of current and light carriers. Such structure is referred to as Separate Confinement Heterostructure. On a monocrystalline substrate, e.g. of GaAs, InP or GaN, a sequence of thin semiconductor layers are created, which was described, among others, in publication by L.A. Coldren, S.W. Corzine, M.L. Mashanovitch, "Diode Lasers and Photonic Integrated Circuits" Wiley Series in Microwave and Optical Engineering, Wiley (2012). The active layer of such devices are quantum wells confined within quantum barriers, and the light is propagated in a slab waveguide made of layers with high refractive index surrounding the active part of the laser, confined by layers with low refractive index. Further on in the present description, the term "diode light-guide" shall relate to a section of the quantum wells area and light-guiding layers surrounding them, where the light is propagated in the device. Lateral confinement for the carriers and light can be obtained in any way (e.g. by means of the following structures: gain guiding or index guiding, such as mesa, buried ridge) without any influence on the generality of the reasoning below. The lateral confinement
results in obtaining high density of light and the carriers in
the active area. The geometry of the device and the additional
antireflective layers prevent light oscillation in the device.
In case of group III metal nitrides based superluminescent
diodes emitting light within the range of 400-500 nm, the said
layers are executed in a characteristic way described, among
others, in publication by S. Nakamura, "InGaN/GaN/AlGaN-based
laser diodes grown on epitaxially laterally overgrown GaN," J.
description. Crystalline gallium nitride 50 to 200 μm thick is
used as the substrate. The cladding layers are made of
gallium-aluminum nitride, Al$_x$Ga$_{1-x}$N, wherein x remains within
the range of 0.05 to 0.12, and the thickness from 0.5 μm to 5
μm. The lower cladding layer is silicon doped at the level of
5x10$^{18}$ cm$^{-3}$. The upper cladding layer is usually magnesium doped
at the level from 5x10$^{19}$ cm$^{-3}$ to 1x10$^{20}$ cm$^{-3}$. The light-guiding
layers are usually made of gallium nitride, from 0.05 μm to
0.15 μm thick. The lower light-guiding layer can be silicon
doped, while the upper light-guiding layer can be magnesium
doped. Both light-guiding layers can also be not doped. For
diodes with emission within 400-500 nm, the electron blocking
layers are made of In$_x$Ga$_{1-x}$N, wherein x is in the range of 0 to
0.15. The quantum well forming layer is made of In$_x$Ga$_{1-x}$N,
wherein x is in the range of 0 to 0.3 and is from 2 to 10 nm
thick. Light guiding is obtained by means of etching selected
regions of the epitaxial structure to the depth not greater
than the border between the upper cladding and the upper light
guide layer. The etching contour is selected in such a way
that the remaining region forms a light fiber that is not
perpendicular to the light guide output facet (crystal
cleavage planes). From the top of the device, electric power
supply is effected solely through the upper surface of the
created mesa (ridge). The superluminescent diode light guide
can have the shape of a skewed or curved strip. The light
guide facet reflectivity is determined by the refractive index values of the light guide, the neighboring area in the layers plane, and the device environment (air or gas used in hermetic assembly) as well as the value of the terminal angle between the light guide axis and the normal to the output facet surface. Moreover, the above-mentioned reflectivity is strongly dependent on the width of waveguide (light guide). These relationships were described in the article by G. A. Alphonse and M. Toda, "Mode coupling in angled facet semiconductor optical amplifiers and superluminescent diodes," J. Lightwave Technol. 10, 215 (1992). The geometry of the light guide is optimized for the fiber optic output facet reflectivity to be the smallest. The basic parameter upon which the superluminescent diode quality is assessed is the shape of the emitted light spectrum. An ideal superluminescent diode has flat emission spectrum like the that of electroluminescent diodes. However, in case of superluminescent diodes, the light is generated due to the amplified spontaneous emission process. For real devices, modulations appear in the spectrum, which increase their depth with the increase of the applied current. They result from oscillation of an amount of light within the volume of the device.

From American Patent Application US 20130308333, a new class of optical light sources is known, built, among others, on the basis of superluminescent diodes. Thanks to only partial covering of the lower and the upper waveguide by cladding layers close to the output facet (unclad waveguide section), lower target feedback was obtained (the light reflected from the output facet, due to the lack of cladding layer of lower refractive index, is scattered in various uncontrolled directions). Furthermore, in order to increase the optical power of the diode, the waveguide is in the form of a strip bent or tilted in relation to the output facet of the
waveguide. In order to provide higher light reflectivity, the waveguide facets were covered, respectively, with a reflective layer, an antireflective layer, a reflective layer with variable reflectivity profile or combination thereof. The presented layers reducing reflections in the light guide facet have the form of thin continuous layers, normally alternating dielectric layers of the thickness of \( \frac{1}{4} \) of the incident radiation wave, which in turn requires complex technological steps in order to deposit them. In order to obtain sub-micrometer dielectric layers of predetermined geometric and material parameters, it is necessary to use such technologies as epitaxy or CVD. The technologies belong to "hi-tech" technologies which makes the whole production process become significantly complex, and the costs of a single device increased. Obtaining dielectric antireflective layers of reflectivity below \( 10^{-6} \) is practically impossible.

On the other hand, Patent Application WO 2011/056675 discloses a superluminescent diode based on III-Nitride, on nonpolar or semipolar GaN substrates. Hexagonal pyramids of the diameter (within the range form 0.1 \( \mu \)m to 10 \( \mu \)m) are formed in wet etching in KOH solution on the surface of the rear mirror of the light guide, providing scattering of light incident upon the rear facet surface. The obtained effect of waveguide facet surface roughness prevents the effect of optical feedback, and by the same the lasing action. Furthermore, the rough surface provides the exponential growth of the output power together with the increase of the current value. Creating this type of reflective layer requires, firstly, depositing the base material by means of complex deposition or growth technologies and then etching the structures of appropriate geometry. Such antireflective layer creation process is complex and requires application of high quality technological apparatus, which results in the increase of a single device manufacturing cost.
The technological problem faced by the present invention is to propose such AlInGaN-based superluminescent diode structure that would be characterized by improved optical parameters, in particular larger width of the emission spectrum and reduced modulation depth in the spectrum, wherein its production would limit the number of necessary technological processes and by the same, the cost of a single device would be reduced. Unexpectedly, the technical problems mentioned above have been solved by the present invention.

The present invention relates to AlInGaN-based superluminescent diode, comprising a semiconductor substrate, a lower cladding layer with n-type electric conductivity, a lower light-guiding layer with n-type electric conductivity, a light emitting layer, an electron blocking layer with p-type electric conductivity, an upper light-guiding layer, an upper cladding layer with p-type electric conductivity, a sub-contact layer doped with acceptors in concentration higher than $10^{20} \text{ cm}^{-3}$, and an antireflective layer deposited on the output facet of the waveguide, characterized in that the antireflective layer contains dielectric nanoparticles whose largest geometrical measurement is smaller than the wavelength of the light emitted by the diode, wherein the diode emits electromagnetic waves in the range from 390 nm to 450 nm. Preferably, the antireflective layer is deposited on an additional oxide layer less than 100 nm thick. Equally preferably, the dielectric nanoparticles constituting the antireflective layer are selected from the group comprising nanoparticles of: SiO$_2$, polystyrene, glass, acrylic glass, wherein the largest nanoparticles size comprises the range from 100 to 250 nm. In a preferred embodiment of the invention, the shape of the waveguide ridge is in the form of a section tilted at the angle between 3 and 8 degrees towards the mirror. In another preferred embodiment of the invention, the waveguide consists of a hundred of segments of increasing
tilt towards a normal to the waveguide facet surface. In another preferred embodiment of the invention, the rear waveguide mirror is covered with a dielectric layer with reflectivity exceeding 80%. Preferably, the lower cladding layer with n-type electric conductivity is an $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer from 200 nm to 500 nm thick, doped with silicon to the level ranging from $5 \times 10^{17}$ cm$^{-3}$ to $5 \times 10^{18}$ cm$^{-3}$, wherein the molar concentration $x$ of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ is within the range from 0.01 to 0.12. Equally preferably, the lower light guiding layer of n-type electric conductivity is doped GaN from 100 nm to 2000 nm thick. Still more preferably, the light emitting layer is a multiple $\text{In}_x\text{Ga}_{1-x}\text{N/In}_y\text{Ga}_{1-y}\text{N}$ quantum well area, wherein the molar concentration $x$ in the quantum well is in the range from 0.03 to 0.1, and molar concentration $y$ in the quantum barrier is in the range from 0 to 0.02, wherein the number of multi-well repetitions is from 1 to 5. In a preferred embodiment of the present invention, the electron blocking layer of p-type electric conductivity is an $\text{Al}_x\text{Ga}_{1-x}\text{N: Mg}$ layer from 5 nm to 30 nm thick, wherein the molar concentration $x$ is in the range of 0.05 to 0.3. In another preferred embodiment of the present invention, the light-guiding layer with p-type electric conductivity is GaN from 100 nm to 2000 nm thick. In another preferred embodiment of the present invention, the upper cladding layer with n-type electric conductivity is an $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer from 300 nm to 1500 nm thick, doped with silicon to the level ranging from $5 \times 10^{17}$ cm$^{-3}$ to $5 \times 10^{18}$ cm$^{-3}$, wherein the molar concentration $x$ of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ compound is within the range from 0.01 to 0.12. In still more preferable embodiment of the present invention, the sub-contact layer is a GaN: Mg layer with magnesium molar concentration higher than $10^{20}$ cm$^{-3}$.

Depositing the antireflective layer in the form of dielectric nanoparticles of uneven surface distribution upon the output facet of the superluminescent diode results in creation of roughness effect on the light-guiding facet, which increases
scattering on that facet, improving light extraction from the device with concurrent prevention of lasing action. The obtained spectra are characterized with greater spectral width and lower spectrum modulation depth. Furthermore, it is possible to apply additional dielectric layers with high reflectance (Bragg mirrors). By increasing the reflectance of the waveguide rear output facet, the reduction of power emitted from that facet is achieved with concurrent increase of the power emitted from the front facet.

Exemplary embodiments of the invention have been presented in the drawings, wherein fig. 1 represents an AlInGaN-based superluminescent diode structure, fig. 2a and 2b represent the possible shapes of superluminescent diode waveguide in top view, fig. 3 illustrates consecutive technological steps to create the mesa, fig. 4 shows the superluminescent diode with the facet covered with antireflective layer, fig. 5 shows a superluminescent diode facet with the antireflective layer deposited, fig. 6 presents a comparison of superluminescent diode emission spectrum with the reflective layer and without one.

Example

The superluminescent diode structure of reduced threshold current, created on GaN substrate is illustrated in fig. 1. The described structure of the device enables emission of light with the wavelength of ca. 415 nm. The presented diode was made in the way described below. In the first step, the GaN substrate 1 was prepared for growing by polishing so as to obtain a parallel-flat plate of typical thickness of 300 μm. The crystal surface with gallium polarity reached, after appropriate polishing, atomic smoothness, demonstrated by atomic steps in the atomic force microscope (AFM) image. The measurement was performed with a NanoScope 4 microscope model from Brucker. The crystal surface was disoriented by at least
0.3° angle in relation to the GaN (wurtzite) hexagonal structure crystallographic axis. Then, substrate 1 was placed in a MOVPE reactor, where layer 2 of Ga0.92Al0.08N 800 nm thick, silicon doped to the level of $5 \times 10^{18}$ cm$^{-3}$ was created at the temperature of ca. 1050°C. Further on, at the same temperature, layer 3 of non-doped GaN, ca. 100 nm thick, acting as the lower waveguide was created. After lowering the temperature to 820°C, In0.1Ga0.9N/In0.02Ga0.98N multi-quantum-well area 4 was created, wherein the number of multi-well repetitions was three. Next, after increasing the reactor temperature to the level of 1050°C, electron escape blocking Al0.02Ga0.98N:Mg layer 5 was performed. After that, the non-doped GaN layer constituting the upper waveguide 6 was created. The next layer was the upper 430 nm thick cladding layer 7 of Al0.05Ga0.95N. The structure growth was completed with thin GaN:Mg subcontact layer 8 with magnesium concentration of $2 \times 10^{20}$ cm$^{-3}$. The cladding and the waveguide layers had their compositions selected in such a way that the refractive index contract between GaN and AlGaN was 1.8%. Having completed the structure growth, the reactor was cooled down in nitrogen atmosphere. In the next step, photolithography was performed by means of a chrome mask contact exposure device. Thus defining the shape of the mesa in the form of a deflected strip, as illustrated in fig. 2b. The terminal waveguide deflection 11 in relation to the crystal cleavage planes (crystallographic plane (10-10), i.e. the plane of the future light-guide output facets 12) was 6°. The mesa and the upper contact creation method was schematically shown in fig. 3. The first technological step was depositing the photoresist layer 9a 3 µm thick upon the designed light-guide area. Then, dry etching of the crystal with active ions (ICP RIE) to the depth of 500 nm took place. This way the mesa in layers 7 and 8 was created, which is illustrated by the diagram in fig. 3b. Further on, a layer of isolating material SiO2 9, 200 nm thick,
was deposited upon the whole crystal, visible in fig. 3c. The layer was deposited with the ICP PECVD method. Due to the large thickness of the photoresist 9a, its lateral edges were not completely covered with the isolator. The top of the mesa was shielded be means of a standard lift-off procedure (fig. 3d) with concurrent leaving the isolator on the lateral walls of the mesa and in the area outside the mesa. The next technological step was depositing, by means of electron beam vapor deposition, the upper 10 and the lower contacts (on substrate 1) made of nickel and gold value with the total thickness of 100 nm. Then, the crystal was divided along the crystal cleavage planes, forming strips containing many devices, wherein the division took place along the designed locations of light-guide facets 12 of the individual devices. The first step enabling the division was scratching the crystal along the planned division line. Next, due to mechanical stress, the crystal was made to break along the cleavage planes. Antireflective layer consisting of dielectric SiO₂ nanospheres was deposited upon the finished device structure. For that purpose, 0.3 ml colloidal solution of nanoparticles were placed in a dispenser, and a drop of the solution was distributed on the front wall of the device. The device was left to dry for 24 hours. The device covered with the antireflective layer is schematically illustrated in fig. 4 and fig. 5a. Fig. 5b, on the other hand, presents the effective shape of the light-guide facet 12. In order to improve the adhesive properties of the nanoparticle-light-guide mirror contact, it is possible to deposit another dielectric layer 15 less than 3 nm thick, which is illustrated in Fig. 5c. The next step was dividing the strips into individual devices, performed in a way similar to the division into strips, not along the crystal cleavage planes, however, but parallel to the latter. The last step was the assembly of the devices in the standard TO-56 housing. A thin layer of
SnPb solder was placed in the housing socket. The device was placed on the latter with the substrate side 1 towards the solder. The annealing process at 200°C enabled durable binding of the device with the socket. Then, the electric contact with the upper contact material 10 was formed by means of ball-bonding. Further on, the superluminescent diode housing was tightly closed using protective atmosphere preventing water condensation inside the housing.

Thanks to the application of the antireflective layer based on dielectric nanospheres, the characteristics of the device were improved as compared to the chips not covered with the said layer. The obtained emission spectra demonstrated shallower modulations than the control device of the same geometry executed in the same process, but with the output life-guide facet 12 uncovered, which was illustrated in fig. 6 presenting a comparison of superluminescent diode emission spectrum with the reflective layer and without one.
Claims

1. AlInGaN alloy based superluminescent diode, comprising a semiconductor substrate (1), a lower cladding layer (2) with n-type electric conductivity, a lower light-guiding layer (3) with n-type electric conductivity, a light emitting layer (4), an electron blocking layer (5) with p-type electric conductivity, an upper light-guiding layer (6), an upper cladding layer (7) with p-type electric conductivity, a subcontact layer (8) doped with acceptors in concentration higher than $10^{20}$ cm$^{-3}$, and an antireflective layer deposited on the output facet (12) of the waveguide, characterized in that the antireflective layer contains dielectric nanoparticles (14) whose largest geometrical measurement is smaller than the wavelength of the light emitted by the diode, wherein the diode emits electromagnetic waves in the range from 390 nm to 450 nm.

2. A superluminescent diode of claim 1, characterized in that the antireflective layer is deposited on an additional oxide layer (15) less than 100 nm thick.

3. A superluminescent diode of claims from 1 through 2, characterized in that the dielectric nanoparticles (14) constituting the antireflective layer are selected from the group comprising nanoparticles of: SiO$_2$, polystyrene, glass, acrylic glass, wherein the largest nanoparticles size comprises the range from 100 to 250 nm.

4. A superluminescent diode of claims from 1 through 3, characterized in that the shape of the waveguide ridge is in the form of a section tilted at the angle (11) between 3 and 8 degrees towards the mirror.

5. A superluminescent diode of claims from 1 through 4, characterized in that the waveguide consists of a hundred of
segments of increasing tilt towards a normal to the waveguide facet (12) surface.

6. A superluminescent diode of claims from 1 through 5, characterized in that the waveguide rear mirror (13) is covered with a dielectric layer with reflectivity higher than 80%.

7. A superluminescent diode of any of claims from 1 through 6, characterized in that the lower cladding layer (12) with n-type electric conductivity is an Al$_x$Ga$_{1-x}$N layer from 200 nm to 500 nm thick, doped with silicon to the level ranging from 5x10$^{17}$ cm$^{-3}$ to 5x10$^{18}$ cm$^{-3}$, wherein the molar concentration x of the Al$_x$Ga$_{1-x}$N is within the range from 0.01 to 0.12.

8. A superluminescent diode of any of claims from 1 through 7, characterized in that the lower light guiding layer (3) of n-type electric conductivity is doped GaN from 100 nm to 2000 nm thick.

9. A superluminescent diode of any of claims from 1 through 8, characterized in that the light emitting layer (4) is a multiple In$_x$Ga$_{1-x}$N/In$_y$Ga$_{1-y}$N quantum well area, wherein the molar concentration x in the quantum well is in the range from 0.03 to 0.1, and molar concentration y in the quantum barrier is in the range from 0 to 0.02, wherein the number of multi-well repetitions is from 1 to 5.

10. A superluminescent diode of any of claims from 1 through 9, characterized in that the electron blocking layer (5) of p-type electric conductivity is an Al$_x$Ga$_{1-x}$N:Mg layer from 5 nm to 30 nm thick, wherein the molar concentration x is in the range of 0.05 to 0.3.

11. A superluminescent diode of any of claims from 1 through 10, characterized in that the upper light guiding layer (6) of
p-type electric conductivity is doped GaN from 100 nm to 2000 nm thick.

12. A superluminescent diode of any of claims from 1 through 11, characterized in that the upper cladding layer (7) with n-type electric conductivity is an Al$_x$Ga$_{1-x}$N layer from 300 nm to 1500 nm thick, doped with silicon to the level ranging from 5x10$^{17}$ cm$^{-3}$ to 5x10$^{18}$ cm$^{-3}$, wherein the molar concentration x of the Al$_x$Ga$_{1-x}$N is within the range from 0.01 to 0.12.

13. A superluminescent diode of any of claims from 1 through 12, characterized in that the subcontact layer (8) is a GaN:mg layer with magnesium concentration exceeding 10$^{20}$ cm$^{-3}$. 
Fig. 5

Fig. 6
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01L33/00 H01L33/44
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)

HO1L

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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X Further documents are listed in the continuation of Box C. X See patent family annex.

* Special categories of cited documents:
- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier application or patent but published on or after the international filing date
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Date of the actual completion of the international search 2 September 2015

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Authorized officer Claessen, Michiel

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