Optica Applicata, Vol. XXXI, No. 2, 2001

Crucial structure elements of possible nitride vertical-cavity surface-emitting lasers

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In the present paper, problems connected with designing possible nitride vertical-cavity surface-emitting lasers (VCSELs) for their efficient room-temperature (RT) operation are discussed and analyzed. Crucial elements of the VCSEL geometry, i.e. active regions, spacers, DBR mirrors, current and heat-flux paths, substrates as well as contacts, are examined in detail taking into account the latest achievements of the currently available technology. An impact of various structure configurations on threshold properties of the possible RT CW nitride VCSELs is discussed and the most recommended structure details are chosen. A possibility to manufacture efficient nitride VCSELs in a close future is considered and discussed.

1. Introduction

Wide bandgap $A^{III}N$ nitride semiconductors, *i.e.*, GaN, AlN, InN nitride materials and their ternary and quaternary solutions, are expected to play a key role in various optoelectronic (OE) technologies in close future because they enable manufacturing completely new semiconductor OE devices for their new very promising applications [1], [2]. Full colour high performance displays (currently the largest one, 120 feet by 90 feet, is situated in the heart of the New Yorks Time Square) and laser printers, high-density information storage on disks using optical methods (*i.e.*, CD and DVD players, video-disk recorders, optical memory systems, *etc.*), underwater military communication systems, high-temperature and/or high-power OE devices, traffic lights and, last but not least, completely new lighting systems (which are believed to replace obsolete electric bulbs in close future and accomplished with the aid of a proper adjusting of constituent LEDs emitting primary colours to yield white light) are the most valuable areas of these new applications. In most of them, standard edge-emitting nitride lasers (EELs) can be used which have just crossed the threshold of commercial availability. However, possible nitride vertical-cavity surface-emitting lasers (VCSELs) could considerably enlarge the range of applications for these wide-bandgap semiconductor OE devices because of their unique properties [3], [4]: high beam quality (circular, narrow, low-divergence, non-astigmatic output beam), ability to be integrated into microelectronic devices and into two-dimensional laser arrays, inherently single-longitudinal-mode operation even in highly dynamic conditions.

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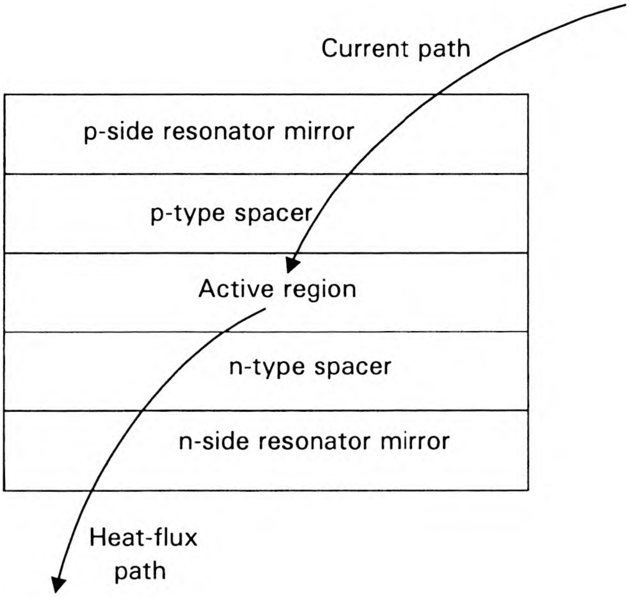
In spite of commercial availability of first nitride EELs announced by Nichia early this year, their manufacturing is still a very involved task mostly because of extremely high densities of defects within their structures and problems with fabrication of smooth highly-reflective resonator mirrors. These difficulties might be resolved in nitride VCSELs. For example, an influence of defects is expected to be much weaker in VCSELs because of relatively small volumes of their active regions [5]. Also high-reflectivity mirrors may be manufactured with the aid of distributed-Bragg-reflectors (DBRs) based on stacks of alternative (of low and high refractive indices) quarter-wavelength semiconducting or dielectric layers. But while nitride EELs are now being produced by a steadily increasing number of technological centers, their electrically-pumped VCSEL counterparts have not been fabricated yet. Manufacturing VCSELs seems to be much more challenging using the nitride compounds than the non-nitride $A^{III}B^{V}$ semiconductors. However, some successful attempts with optically-pumped nitride VCSELs have been reported (*e.g.*, [6] – [11]) and some symptoms of preliminary designing of electrically-pumped nitride VCSELs can be found in scientific literature [12] – [17]. Theoretical analysis [18] – [25] confirms the possibility of RT operation of nitride VCSELs.



Crucial VCSEL structure elements.

The main goal of this paper is to consider a possibility to manufacture nitride VCSELs for their room-temperature (RT) continuous-wave (CW) operation using currently available technology. To this end, the latest achievements useful in producing these devices and reported by various technological centres are analysed.

Crucial structure elements of nitride VCSELs, *i.e.*, active regions, spacers, DBR mirrors, current paths, heat-flux paths, contacts and substrates (see Figure), are discussed in the following sections of the paper.

2. Active regions

Currently there are two possible configurations of active regions in nitride VCSELs depending on a desired radiation wavelength, namely VCSELs with the InGaN/AlGaN quantum wells (QWs) for blue, green and violet light emission as well as VCSELs with the GaN/AlGaN QWs for ultraviolet (UV) emission. The third possibility, *i.e.*, UV-emitting VCSELs with the InAlN active layer, is a much worse solution since a very high AlN content would be necessary to match GaN layers.

2.1. InGaN active layers

At present, most of nitride emitters are equipped with InGaN active layers. These devices are known to emit surprisingly bright luminescence in spite of the density of threading dislocations up to 10^{10} cm^{-2}. It is directly associated with their very efficient stimulated recombination taking place between carriers localized by large potential fluctuations in the InGaN layers [26], [27], so-called self-assembled quantum-dot (QD) indium-rich nanoscale structures, due to difficulties in a uniform In incorporation [28], [29]. For carriers localized into the QDs, their migration toward non-radiative centres is no longer allowed, and, provided that the dots are defect-free, carriers have to recombine radiatively. The gain in the InGaN/AlGaN lasers is therefore strongly related to the structure of indium composition fluctuations. Under low injection conditions, carrier localization is a dominant feature for electronic transport in the InGaN layer, higher injection levels, however, will increase also an importance of extended (nonlocalized) states for laser operation [29], [30]. The effectivity of an interaction between carriers confined within gain active layers and the optical field is described by the confinement factor. This factor is very low in single quantum well (SQW) structures but is becoming steadily higher with an increase in a number of QWs in multiple quantum well (MQW) active regions. Therefore in nitride laser technology usually MQW active regions are used, sometimes containing even more QWs than 10. Then carrier injection into successive QWs of a MQW structure may be apparently nonuniform [31], [32], distinctly reducing device efficiency. This nonuniformity should be additionally taken into consideration in MQW laser designing.

2.2. GaN active layers

Unfortunately, potential fluctuations in the AlGaN layers analogous to those in the InGaN layers are not expected to enhance radiative recombination [33] in GaN/AlGaN QWs lasers. An optimal doping concentration was found to be around $5 \cdot 10^{17}$ cm^{-3} for stimulated emission in a bulk GaN [34]. Similar value is expected for QW GaN/AlGaN active regions. In MQWs GaN/AlGaN structures, an optimal quantum-well width was found to be contained between 12 Å and 42 Å [35]. From narrower QWs an enhanced carrier leakage is observed, whereas in wider QWs an increased nonradiative recombination takes place. The optimal number of QWs is proportional to the total optical losses [36]. Therefore, for currently available nitride technology, MQW active regions are much more suitable for GaN/AlGaN VCSELs than SQW ones. The optimal growth conditions for the above MQWs are GaN-like rather than AlGaN-like or any other condition [37]. To improve active-region crystal quality, isoelectronic doping with In is used [38]. This improvement is thought to be associated with the solid solution hardening effect: an impurity atom is incorporated into dislocations where it serves to pin their gliding. Besides, isoelectronic doping can effectively suppress the formation of deep levels [39] as well as reduce the mismatch-related strain [40], [41].

2.3. Piezoelectric effect

$A^{III}N$ nitrides exhibit an enormously high piezoelectric effect [42]. Therefore the mechanical strain created in nitride structures because of a lattice mismatch between their successive layers becomes a source of huge internal built-in electric fields, sometimes as high as over 1 MV/cm [43]–[45]. Additionally, strong polarization effects are still present in nitride structures even without any strain [44], [46] due to the difference between spontaneous polarizations in successive layers. This combined built-in electric field is pulling holes and electrons in opposite directions because of their different charge. It produces some separation between electron and hole wave functions for carriers confined within the same QW, which is followed by lowering their overlap integral and an optical gain. This effect is more pronounced in nitride structures with wider QWs, which suggests that thin well widths below 30 Å are desirable in these devices [44]. Besides, the induced electric field is larger in a SQW nitride structure than in a similar MQW structure [47]. Moreover, the piezoelectric effect also produces a surface dipole at heterointerfaces. It decreases the potential barrier influencing considerably electron transport in nitride heterojunction devices [48], [49].

Additionally, Coulomb interaction effects also play an important role. While potential profiles and optical gain are significantly affected by the piezoelectric field in nitride heterostructure devices at relatively low carrier densities, their optical properties become very similar to those without any built-in electric field at high injection level due to the screening effects [50]. Therefore the piezoelectric effect is believed to be negligible in diode lasers for currents exceeding their lasing thresholds.

3. Spacers

In conventional diode lasers, *i.e.*, in arsenide and phosphide ones, designing of spacers is relatively simple. They should only be wide enough (to reduce carrier leakage from an active region) and doped to a level not too high (because of the free-carrier absorption) and not too low (because of their electrical resistivity). Furthermore, they should exhibit high thermal conductivity to provide an efficient heat extraction from active regions. In nitride VCSELs, spacers should be chosen much more carefully, mostly because of problems with their p-type doping. Lasers with the GaN active layers require AlGaN or AlN claddings. In the case of the InGaN active medium, also the GaN claddings could be considered.

Because of a very large bandgap of AlN (6.2 eV at RT) and its very low index of refraction (2.21 at RT), even an $Al_xGa_{1-x}N$ cladding layer of a relatively low mole fraction x ($x \sim 0.1$) ensures an efficient confinement of carriers and an electromagnetic field. The above fact is a very fortunate opportunity because the $Al_xGa_{1-x}N$ electrical resistivity is increasing very quickly with an increase in x (*e.g.*, resistivity of the $Al_{0.1}Ga_{0.9}N$ is about one order of magnitude higher than that of GaN [51]).

While n-type doping of nitride layers is already carried out efficiently, there are still some problems with their effective p-type doping. Currently magnesium dopant is mostly used in GaN and AlGaN layers to create their p-type conductivity. Unfortunately, they usually show high electrical resistivity, which is a result of both the deep nature of the Mg acceptor and a low hole mobility. The postgrowth treatment by low energy electron irradiation (LEEBI [52]) or thermal annealing in N_2 ambient [53] is required to activate their p-type conductivity. Nevertheless, only a small fraction of all electrically active Mg acceptors donate a hole at RT because of their high activation energies (260 meV [54] in moderately Mg -doped GaN, which is steadily reduced with an increase in doping to 112 meV for $2 \cdot 10^{20}$ cm^{-3} [55]). These ionization energies are even higher in AlGaN [56]. Many other acceptor candidates (Li, Na, K, Zn, Ca, C, *etc.*) for GaN have been considered [56], [57], but only Be emerges as a potential alternative dopant (see below). Paradoxically, high resistivity of p-type nitride layers is reduced in CW-operating VCSELs because of a temperature increase and hence an increase in activation of deep acceptor levels.

Recently, AlGaN/GaN superlattices have been proposed [58] for cladding layers in nitride lasers instead of the bulk AlGaN films. Superlattice modulation doping can enhance at RT the average hole concentration by more than nine orders of magnitude [59], [60]. Using this procedure, RT hole concentrations as high as $2.5 \cdot 10^{18}$ cm^{-3} and electrical resistivities as low as 0.2 Ωcm have been achieved [60]. Besides, these superlattices can reduce unwanted strain in nitride heterostructures [61], formation of cracks and even diode operating voltage [62].

Quite a different method has been used to enhance electrical resistivities of nitride cladding p-type layers by BRANDT *et al.* [63]. They applied in cubic GaN Be as the acceptor species and O as reactive donor to render isolated Coulomb scattering into dipole scattering. Residual O donors and Be acceptors are spatially correlated in the form of ion pairs. Such BeO complexes are much less effective in the scattering of holes, therefore their RT mobilities are surprisingly high. For Be and O doping in almost equal amount of about $5 \cdot 10^{20}$ cm^{-3}, a RT hole concentration of 10^{18} cm^{-3}, hole mobility of 150 cm^2/Vs as well as electrical resistivity of only about 0.02 Ωcm have been reported [63]. This procedure is probably possible also for hexagonal GaN doped with Mg and co-doped with O [63].

Similarly as in all other semiconductor lasers, active layer heating remains one of the main heat sources in a nitride laser. But because of their relatively high electrical resistivities, the Joule heating in nitride cladding layers influences thermal properties of a device to a comparable extent. Additionally, cladding layers play a dominant role in heat extraction mechanism. Fortunately, thermal conductivity of nitride layers is surprisingly high (compared to other $A^{III}B^{V}$ materials). For GaN layers, its RT values exceeding 130 W/mK have been reported [64]–[68] with the highest value of 195 W/mK [69]. Analogous RT conductivity for AlN ranges from 200 W/mK [64], [65] to 280 W/mK [67] and that for InN is roughly estimated to be equal to 80 W/mK [67], [70]. Obviously, in ternary alloys these values are considerably lower [22], [71].

4. Resonator mirrors

The VCSEL configuration enables us to use distributed Bragg reflectors (DBRs) as resonator mirrors. They are composed of many alternating (low- and high-refraction -index) layers of strictly defined thicknesses equal to the quarter of the radiation wavelength. Any change of their thicknesses, even slight thickness nonuniformities, is followed by a decrease in the effective mirror reflectivity because of scattering phenomena. Also possible absorption of radiation within DBR layers reduces this reflectivity. Therefore, in manufacturing efficient VCSELs it is essential to reduce a number of their DBR periods to suppress the possibility of an introduction of unwanted structure imperfection. Maintaining the same high mirror reflectivity for a reducing period number needs, however, an increase in a step change of an index of refraction between alternating DBR layers. Unfortunately, AlN and GaN layers exhibit similar values of refractive indices ($n_{AlN} = 2.21$ and $n_{GaN} = 2.74$ [65], [72], [73]). Therefore, assuming the GaN high-index layers, nitride DBRs need very high AlN content in the low-index layers. Preferably, from an optical point of view, they should have the AlN/GaN structure, which, however, has an extremely high electrical resistivity. In fact, these AlN/GaN DBR mirrors would exhibit additionally high absorption of a laser radiation [73]. Therefore, their GaN layers should be replaced with, *e.g.*, $Al_{0.15}Ga_{0.85}N$ layers, whose band gap is much larger. Theoretically, such DBR mirrors exhibit reflectivity as high as over 99% for more than 20 periods and over 99.5% for more than 30 periods [18]. Unfortunately, scattering and absorption losses in real nitride DBRs can considerably reduce their effective reflectivities. Nevertheless nitride DBR mirrors of reflectivities over 95% have been routinely manufactured [9], [74]–[78], these reflectivities may, however, be still too low for efficient nitride VCSELs. The problems that additionally arise in epitaxial growth of multilayered nitride structures are the large difference in thermal expansion coefficients between GaN ($5.6\cdot10^{-6}$ K^{-1}) and AlN ($4.2\cdot10^{-6}$ K^{-1}) and the large difference in their lattice constants (2.7%) [79]. Besides, it seems to be much easier to produce analogous or even better dielectric mirrors. From an electrical point of view, they are isolators. But this does not seem to be essentially disadvantageous, because AlAs layers in nitride DBR mirrors are also nearly isolators, so anyway current paths avoiding penetration of DBR layers should be designed in nitride VCSELs. Unfortunately, dieletric layers also exhibit very poor thermal conductivity, which should be additionally taken into account in designing CW-operating lasers. HONDA *et al.* [80] have reported the SiO_2/TiO_2 DBR reflectors of a reflectivity of over 96% for 493 nm. Even higher values have been achieved recently: 99.5% for the ZrO_2/SiO_2 structures for 399 nm [78], [81] as well as over 99.9% for the SiO_2/HfO_2 structures in the 420 nm range [10], [14], [16]. Such high reflectivities are still not available in nitride DBRs, therefore dielectric mirrors should now be recommended for possible CW-operating nitride VCSELs with some additional heat-flux extraction mechanisms.

5. Current paths

In complex multilayered structures of diode lasers, current paths should be carefully designed to lead electrons and holes from both electrical contacts directly to active regions and not to let them to penetrate other regions. In conventional diode lasers, manufactured from $A^{III}B^{V}$ arsenides or phosphides, current paths are created using etching of unwanted regions, drastically increasing their electrical resistivities or introducing reversely biased p-n junctions. Especially efficient is the technology of radial oxidation of AlAs layers transferring them into high-resistivity Al_xO_y material [82]. Unfortunately, no such technology that would allow similar achievements is currently known for nitrides, although reports of some first attempts in this area have already been published [83]. Lateral current confinement can, however, be accomplished in nitride VCSELs using selective doping of cladding layers: high enough in their central parts and negligible elsewhere. Alternatively, the LEEBI technique [52] may be used selectively to activate p-type conduction only within the central part of the VCSEL structure. The simplest and currently probably the most efficient method, however, seems to be the ion implantation technique [84] – [87] used to create lateral high-resistivity areas funneling current directly to the central active region. After damage caused, for example, by H^+ or He^- ions passing through the nitride layer, an increase in its electrical resistivity by as many as 11 orders of magnitude has been demonstrated [85]. An important feature of this method is that it leaves some upper part of bombarded region practically unaffected, which enables supplying the central device region with radial current flows. Technologically, much more difficult, is the structure of the index-guided nitride VCSELs [88] where high-resistivity AlN (or high AlN-content AlGaN) layers are applied to confine both the current flow and the radiation field. Currently, however, their manufacturing is probably beyond technological possibilities.

Etching is an important process in the fabrication of optimal device structures. It is used to enable more advanced structure modifications. Although nitrides have unusual chemical stability that makes them difficult to etch, successful dry etching techniques using high density plasma have been reported and various wet chemical etching processes have been demonstrated (*e.g.*, [89] – [92]). Alternatively, the photoenhanced chemical etching processes have been investigated in order to obtain higher etching rates and more smoothly etched nitride surfaces [92]. For example, using the KOH etching solution, the Hg lamp illumination and biasing the substrate with a negative voltage of -10 V, the etching rate as high as 2.1 μm/min has been reported for GaN [93].

Successful designing of diode lasers needs also effective methods of surface passivation especially using oxidation. Due to the lack of native oxidation techniques on GaN, usually SiO_2 or Si_xN_y are deposited as dielectric coatings [94]. Recently, gallium oxide of very low refractive index has been reported as a promising candidate used to passivate GaN surfaces [95].

6. Heat-flux paths

An efficient heat-flux extraction mechanism is important for CW-operating lasing devices because increasing temperature within their volumes deteriorates the effectivity of energy exchange between carriers and an optical field. With an increase in temperature, material optical gain is reduced, absorption losses are increased, electrical resistivity usually increases (but not in p-type nitrides, *cf.* Section 3), heat generation is usually enhanced and its efficient extraction becomes obstructed. Therefore, both suppresion of heat-generation mechanisms and improving effectivity of heat-extraction paths are essential for RT CW-operating diode lasers. Fortunately, nitride materials exhibit surprisingly high thermal conductivity (*cf.* Section 3). Besides, proton implantation is believed not to deteriorate this conductivity. Therefore, formation of current paths using this method does not disturb effectivity of the mechanism of two-dimensional heat extraction from active regions. Some problems may appear because of very low thermal conductivities of dielectric mirrors. Therefore, the device design should enable heat flux to avoid crossing dielectric layers.

In conventional diode lasers, heat generation within their active regions (this generation is mostly associated with nonradiative recombination and reabsorption of spontaneous radiation) is decisively the most intense heat source. In analogous nitride lasers, even more important is the Joule heating in the semiconductor layers (especially in the p-type layers). This generation may be reduced by enhancing acceptor dopants, which has been described in Section 3. It is interesting to note that this generation is reduced at higher temperatures. Also the Joule heating at the p-side contact is of importance, which is described in Section 7. An influence of all other heat generation mechanisms is negligible.

7. Contacts

Until now, many various ohmic contacts have been elaborated for nitride structures [96], including even high-transparency contacts [97], [98]. But while low-resistivity contacts on n-GaN are now routinely fabricated, no satisfying contacts to p-GaN have been developed so far. The former ones of as low resistivity as $3.6 \cdot 10^{-8}\ \Omega\mathrm{cm}^{-2}$ have been reported [99], whereas the lowest achieveable resistivities of the latter ones are still three orders of magnitude higher [100]–[103].

8. Substrates

Initially, nitride laser structures have been fabricated mostly on sapphire (Al_2O_3) substrates. Sometimes also other substrate materials have been used, *e.g.*, gallium arsenide (GaAs), silicon (Si) and even such exotic ones as $RbIo_3$ or CdGaInO. But only silicon carbide (SiC) substrates have ensured comparable or sometimes even better results than sapphire ones, especially for the continuous-wave operation because of their very high thermal conductivity [22]. All of them suffer, however, from mismatch related phenomena, resulting in as high as 10^9 to $10^{10}\ \mathrm{cm}^{-2}$ threading dislocations densities [104]. Besides, large difference in thermal expansion coefficients may be a source of a steadily growing defect density. It is also difficult to grow thick AlGaN cladding layers required for optical confinement, due to the formation of cracks during the growth of the layers. These cracks are caused by the stress introduced in the cladding layers as a result of a large lattice mismatch and the above differences in thermal expansion coefficients.

Improvement in crystal quality of manufactured nitride structures requires elimination of dislocations and other defects. It needs the development of new substrates with a good match of lattice constants and thermal expansion characteristics to nitrides, on which defect-free nitride layers can be grown directly [12]. Only GaN substrate can fulfil both these requirements. It is, however, very difficult to be manufactured, because it has to be fabricated under an extremely high pressure. Nevertheless, some time ago gallium nitride substrates became available in the High Pressure Research Center in Warsaw (these achievements have been reviewed in [105]). More recently, the ELOG (epitaxially laterally overgrown) method has been developed [106] reducing the dislocation density to as low as only 10^4 to $10^5\ \mathrm{cm}^{-2}$ range [107]. A method that is even better for obtaining "pure" GaN substrates consists in growing a thick ($\sim 100\ \mu\mathrm{m}$) GaN layer on the ELOG structure and removing the sapphire substrate by polishing it [108] or by illuminating the interface with a pulsed ultraviolet laser that induced localized thermal decomposition of the GaN crystal [109], [110].

9. Conclusions

Until now, RT operation of electrically-pumped nitride VCSELs has not been reported, which is obvious considering their tough structure requirements. Current challenges facing efforts to realize nitride VCSELs resemble those encountered earlier with the conventional $A^{III}B^{V}$ compounds. On the one hand, excellent nitride light-emitting diodes and quite good edge-emitting lasers have been reported [111]; on the other hand, nitride VCSELs are still too difficult to manufacture. But an urgent need for compact laser sources emitting in blue and UV range of spectrum and additionally exhibiting a dynamic longitudinal single-mode operation, a circular non-astigmatic low-divergent output beam and vertical architecture suitable for integration with other electronic devices together with steadily improved quality of nitride technology raises our hope for a rapid technological development aiming at manufacturing these promising devices. Very recently, for example, a vertical injection nitride light-emitting diode has been reported [14], [15], [17], [112]. Its geometry resembles that of VCSELs. Also much more involved technologically nitride structures containing VCSELs have been proposed (see, *e.g.* Fig. 60 in Ref. [113]). Optically-pumped nitride VCSELs have been reported many times (see, *e.g.*, [8] – [10], [23]). Also some simulations of an RT operation of nitride VCSELs and their designing attempts have been reported [13], [18] – [25], [87]. So fabrication of nitride VCSELs for their efficient RT operation may turn out to be closer than it is generally thought.

Acknowledgments – This work has been supported by the Polish State Committee for Scientific Research (KBN), grants Nos. 7-T11B-069-20, 7-T11B-073-21, 8-T11B-025-17 and 8-T11B-018-12, as well as by the US – Poland Maria Skłodowska-Curie Joint Fund No. MEN/NSF-98-336.

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Received October 9, 2000