Published in: phys. stat. solidi (c) **6**, No 2, 603–606 (2009) / **DOI** 10.1002/pssc.200880405

Effects of electron and optical confinement on performance of UV laser diodes

K. A. Bulashevich[1,2], M. S. Ramm[1], and S. Yu. Karpov[*,1]

[1] STR Group–Soft-Impact, Ltd., P.O.Box 83, 27 Engels av., St.Petersburg, 194156 Russia
[2] Ioffe Physico-Technical Institute RAS, 26 Polytekhnicheskaya str., St.Petersburg, 194021 Russia

Received 6 August 2008, revised 24 September 2008, accepted 24 September 2008
Published online 12 November 2008

PACS 42.55.Px, 71.55.Eq, 78.20.Ci, 78.45.+h

Using simulations accounting for birefringence of III-nitride materials, we studied the laser diodes emitting light at 360-380 nm, which was controlled by adjusting the InGaN composition in the multiple-quantum well active region. Both electron and optical confinement in the LD heterostructures are found to depend strongly on the quantum well composition and affect remarkably the threshold current of the diodes. In particular, the electron leakage from the active region becomes considerable at low InN contents in the quantum wells. The waveguide mode penetration beyond the nominal waveguide layers results in remarkable variation of the optical confinement factor with the emission wavelength and switching between different lateral modes. The above effects provide explanation of the observed three-fold increase in the threshold current density of the LDs upon small changes of the quantum well composition.

Preprint 2008

1 Introduction III-nitride visible and ultra-violet (UV) laser diodes (LDs) are greatly demanded for a number of applications, including high-density CD-ROM and magneto-optical data storage, next generation of DVD players, high-resolution printing, spectroscopy, material processing, etc. Because of technological reasons, the III-nitride LD heterostructures are made asymmetric, i.e. with *p*-layers normally thinner than *n*-layers. Along with a small variation of the refractive index in III-nitride ternary and quaternary alloys, this results in a poor optical confinement affecting the threshold current of the LDs. Another relevant problem is the electron leakage in the *p*-region of a laser heterostructure, which becomes important at high current densities typical of the III-nitride LD operation.

In this paper we report on the theoretical study of electron and optical confinement in near-UV laser diodes aimed at better understanding of their impact on the device performance.

2 Laser structure and simulation approach We consider the LD structure demonstrated in [1] as a representative case. The LD structure was grown on sapphire substrate and contained an active region comprised of five 3.5 nm $In_xGa_{1-x}N$ quantum wells (QWs) separated by 7 nm $In_{0.01}Al_{0.16}Ga_{0.83}N$ barriers. The emission wavelength was controlled by fitting the QW composition x ranged between 0.002 and 0.027. Parameters of other layers and general LD design are described in [1] in detail. These LDs exhibit a dramatic, more than three-fold, variation of the LD threshold current with the emission wavelength, despite extremely low InN content in the QW active region.

Simulation of the LD operation was performed with the SiLENSe 3.42 package [2] considering both the carrier transport in the heterostructure and electromagnetic wave propagation. The modeling of TE- and TM-modes in the waveguide was carried out with taking into account (i) birefringence inherent in III-nitride materials and (ii) metallic electrodes on top of the LD structure. The former was important, as the difference between the ordinary and extraordinary refractive indexes is comparable with their varia-

* Corresponding author: e-mail sergey.karpov@str-soft.com, Phone: +7 812 554 4570, Fax: +7 812 26 6194

tion across the heterostructure. The later is necessary because of relatively thin *p*-regions used in the LDs. In more detail, the waveguide model is presented in [3].

We assumed the LD structure to be fully strained relatively to the 4 μm *n*-GaN contact layer grown on sapphire substrate. The short-period superlattice claddings used in the actual LD structure were substituted by uniform AlGaN layers with average composition while modeling. The threading dislocation density of 2×10^8 cm^{-2} was also assumed in all the layers to find the carrier life times related to their non-radiative recombination at the dislocations [4].

To account for the wide-range spectral dispersion of the materials optical properties, we used the approximation of the complex dielectric constants in the form

$$\varepsilon(E) = \varepsilon_\infty + A\frac{i\Gamma E}{(E_g - i\Gamma)(E - E_g + i\Gamma)} + B\frac{E_1^2}{E_1^2 - E^2 - i\gamma E} \quad , \tag{1}$$

where E is the photon energy, E_g is the semiconductor bandgap, and E_1 is the energy corresponding to the main peak in the optical density of states. The dielectric constant ε_∞, magnitudes A and B, and damping constants γ and Γ were fitted separately to the data on the ordinary and extraordinary dielectric functions of GaN, AlN, and InN available in literature. For ternary and quaternary compounds, a linear interpolation of the parameters was used. The expression (1) enables an accurate approximation of the dielectric constant and, hence, refractive index at the energy E close to the materials bandgap.

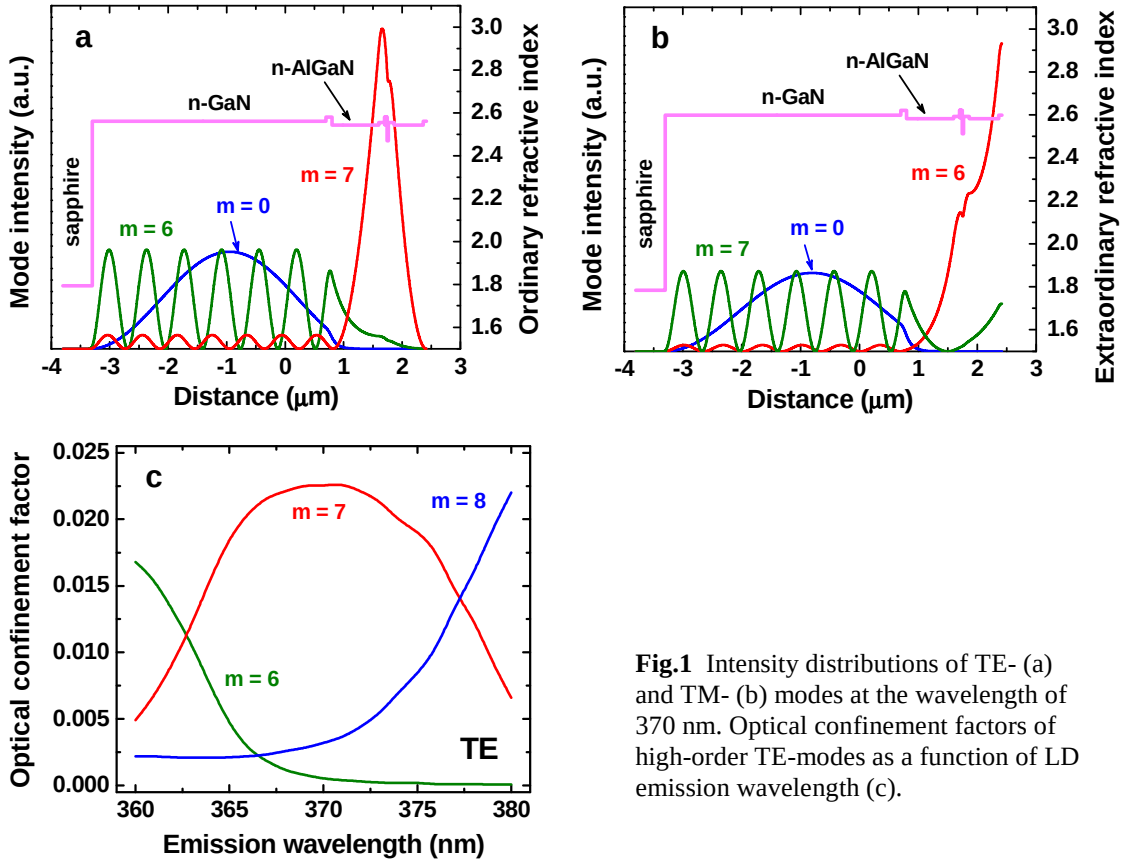

Fig.1 Intensity distributions of TE- (a) and TM- (b) modes at the wavelength of 370 nm. Optical confinement factors of high-order TE-modes as a function of LD emission wavelength (c).

3 Optical confinement Our simulations show that more than a hundred lateral waveguide modes may exist in the LD heterostructure. Because of the structure asymmetry and small refractive index variation in the waveguide and cladding layers, most of the modes are localized or penetrate deeply in

the *n*-GaN contact layer (see Fig.1). Only the TE-mode of the seventh order (m = 7) has the maximum optical confinement factor (OCF) at the emission wavelength of 370 nm (Fig.1a). This mode is not completely confined, however, in the waveguide but oscillates in the contact layer. Some TM-modes are predicted to be localized at the metallic electrode on top of the heterostructure (Fig.1b), which is due to specific boundary conditions at the metal-semiconductor interface [3].

The penetration of the high-order modes in the *n*-GaN contact layer leads to a high sensitivity of their OCFs to the emission wavelength (Fig.1c). Thus the increasing InN content in the QWs from 0.2 to 2.7% results in switching between the lateral modes and, hence, in a large variation of the maximum OCF, from 1.1% to ~2.3%. The latter affects considerably the threshold current of the LDs. The TM-modes are predicted to have typically smaller OCFs and higher free-carrier optical losses. Therefore, they do not reach the oscillation threshold.

We have also found that the OCF of a selected mode can be easily optimized for a given emission wavelength by adjusting the thickness of the contact layer.

The LD structure asymmetry and the use of a high-AlN content electron blocking layer between the active region and *p*-waveguide layer result in a shift of the intensity maximum of the seventh-order TE-mode relative to the active region. This means that an accurate design of the waveguide and cladding layers would allow further optimization of the LD heterostructure.

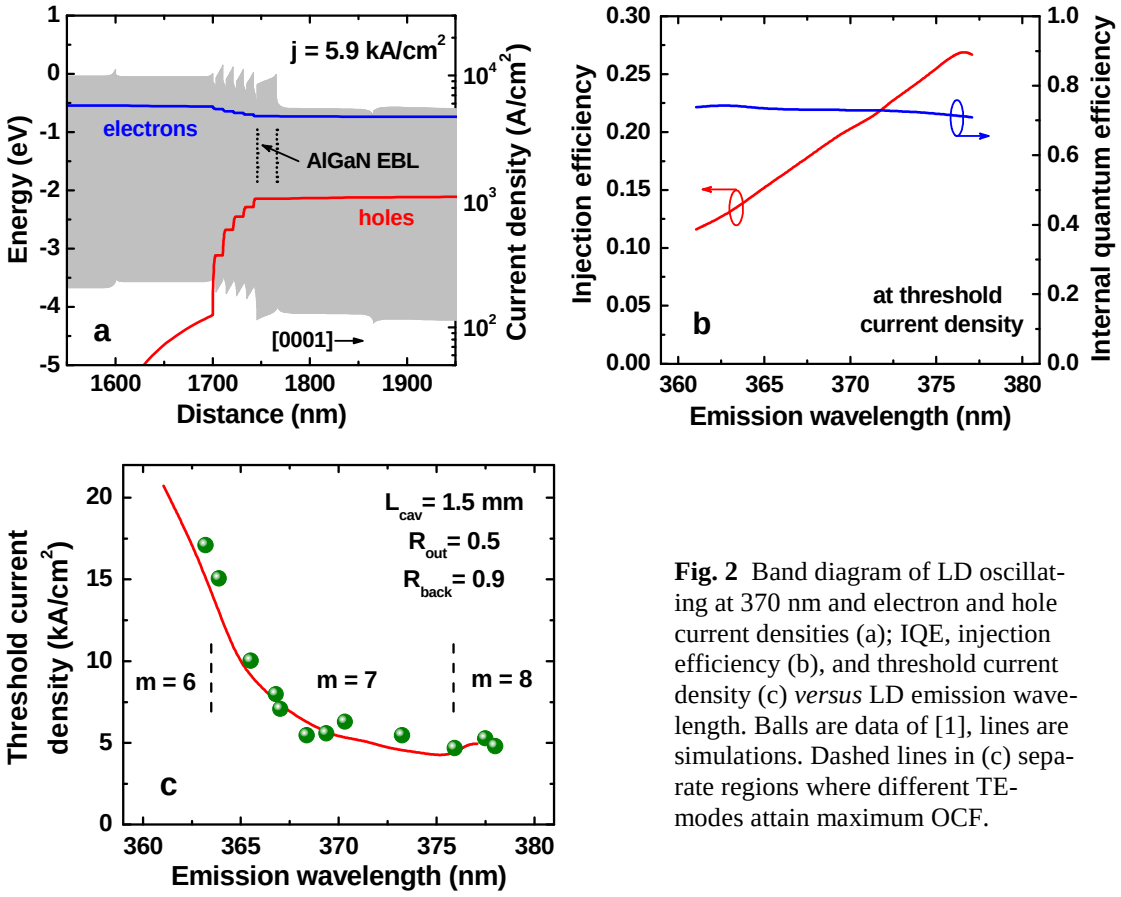

Fig. 2 Band diagram of LD oscillating at 370 nm and electron and hole current densities (a); IQE, injection efficiency (b), and threshold current density (c) *versus* LD emission wavelength. Balls are data of [1], lines are simulations. Dashed lines in (c) separate regions where different TE-modes attain maximum OCF.

3 Electron confinement and threshold current Laser diodes operating at high current densities frequently suffer from the electron leakage in *p*-regions of the devices. This is, in particular, demonstrated by Fig.2a where the band diagram of the LD oscillating at 370 nm is shown along with the distributions of partial electron and hole current densities in the heterostructure. The imbalance between the

electron and hole currents is just caused by strong electron leakage which cannot by effectively suppressed by the $Al_{0.3}Ga_{0.7}N$ electron blocking layer (EBL) because of insufficiently barrier height.

To estimate quantitatively the effect of the electron leakage, we plot in Fig.2b the internal quantum efficiency (IQE) of the LD heterostructure and its injection efficiency. The IQE, i.e. the ratio of the radiative recombination current to the total current in the QWs, is found to weakly depend on the QW composition and, hence, on the emission wavelength. In contrast, the injection efficiency, defined as the ratio of the total recombination current in the QWs to the total current flowing through the structure edges, varies considerably with the wavelength. Actually, from 73 to 90% of all electrons become lost for light generation. The leakage losses are especially strong in the short-wavelength LDs having more shallow QWs.

Both the insufficient electron confinement resulting in the leakage losses and poor optical confinement are the principal factors having comparable impacts on the LD threshold current density, as shown in Fig.2c. The dramatic current density decrease with the emission wavelength can be explained in terms of simulations, accounting for these factors and their dependence on the QW composition.

An alternative explanation of the above effect given in [1] invokes increasing absorption losses in the waveguide as the oscillation wavelength gets closer to the absorption edge of, first of all, *n*-GaN contact layer. We could not examine this effect by modeling because of lacking reliable data on the spectral dependence of the absorption coefficient near the bandgap of *n*-GaN. This issue is the subject of further studies.

4 Summary In this paper, we studied the mechanisms determining performance of near-UV LDs. The modelling of the electromagnetic field predicts existence of many lateral modes, most of which are confined between the sapphire substrate and metallic *p*-electrode, rather than in the waveguide imbedded in the heterostructure. Because of this, the OCF of the mode first reaching the threshold conditions becomes quite sensitive to variations of the emission wavelength. Nevertheless, the confinement factor can be optimized by adjusting the thickness of the *n*-GaN contact layer first grown on the substrate. The OCF estimated from simulations are in the range of ~1.0-2.2%, which is less than the value typical of the LDs made from conventional III-V compounds.

The electron leakage in the LD structures at the threshold current density is large despite the utilization of special EBL in the LD structure. Both the electron leakage and spectral dependence of the OCF are found to be the factors largely affecting the threshold current density of the LDs. Good agreement between the theoretical predictions and observations made in [1] suggest simulation to be an effective tool for optimization of the LD heterostructures.

Acknowledgements The work of K.A. Bulashevich was supported in part by the Russian Federal Program on Support of Leading Scientific Schools and Russian Foundation for Basic Research (grant 05-02-16679).

References

[1] M. Kneissl, D. W. Treat, M. Teep, N. Miyashita, and N. M. Johnson, Appl. Phys. Lett. **82**, 2386 (2003).
[2] http://www.semitech.us/products/SiLENSe/
[3] T. E. Slobodyan, K. A. Bulashevich, and S. Yu. Karpov, Semiconductors **42**, 845 (2008).
[4] S. Yu. Karpov and Yu. N. Makarov, Appl. Phys. Lett. **81**, 4721 (2002).