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Waveguide Design for Long Wavelength InGaN Based Laser Diodes

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One-dimensional optical waveguide calculations were performed to study the dependence of waveguide design on confinement factor ($\varGamma$) and optical losses (α_i) of nitride laser diodes for emission wavelength ranging from 405 nm to 520 nm. We found that the conventional waveguide design containing GaN waveguide and AlGaN cladding layers known from violet laser diode does not support sufficient confinement of the optical mode for long wavelength devices ($\lambda > 450$ nm). We proposed a new design consisting of a thick InGaN waveguide which enhances the confinement. We compared the theoretical predictions with laser diodes grown by plasma assisted molecular beam epitaxy.

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1. Introduction

Recently, the fabrication of nitride based laser diodes (LDs) with emission wavelength ranging from UV up to green became very intensively studied due to their potential impact on optoelectronics e.g. laser projectors, solid state lightening [1–3]. One of the key challenges in producing efficient InGaN based LDs is the waveguide design. There are some recent experimental works studying the influence of waveguide design on LD characteristics for wavelengths up to 440 nm. Ryu et al. [4] showed the influence of n-AlGaN cladding composition on electrical properties of LDs. Strauss et al. [5] investigated the influence of thickness of n-AlGaN cladding on optical beam quality. There are also some theoretical works giving a survey in waveguide design for blue and green LDs [6, 7].

In this paper we use a one-dimensional optical waveguide model to study the properties of optical modes in separate confinement heterostructure violet, blue and green LDs. We show a drop of confinement factor with wavelength. We investigate the role of InGaN waveguide and propose it as a solution to compensate the drop. Results are compared with characteristics for LDs operating at 450 nm grown by plasma assisted molecular beam epitaxy (PAMBE).

2. Method

For the calculations we use a 1D transfer matrix method [8]. The refractive index model of AlGaN alloys is taken from Ref. [9]. Due to a lack of refractive index data for InGaN, we apply the procedure of Bergmann and Casey [8] and shift the energy scale of GaN refractive index

$$n_{\mathrm{InGaN}}(x,E) = n_{\mathrm{GaN}}\{E - [E_{\mathrm{g}}(x) - E_{\mathrm{g}}(0)]\}$$

with $E_{\mathrm{g}}(x)$ being the band gap energy of $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{N}$ alloys [10]:

$$E_{\mathrm{g}}(x) = 3.42(1-x) + 0.77x - 1.43x(1-x).$$

The absorption coefficients used for the calculations are 125 cm^{-1} for electron blocking layer (EBL) and contact layer, 25 cm^{-1} for Mg doped layers, 10 cm^{-1} for Si and unintentionally doped layers [6]. Refractive index and absorption coefficient of Au have been taken from Ref. [11].

The confinement factor is defined as the ratio of the mode in the quantum wells (which is the part generating optical gain) and the mode integrated over the whole structure divided by number of quantum wells

$$\varGamma = \frac{1}{N_{\mathrm{QW}}}\frac{\int_{\mathrm{QW}}|E(x)|^2\,\mathrm{d}x}{\int_{-\infty}^{+\infty}|E(x)|^2\,\mathrm{d}x}.$$

Optical losses of j-th layer are defined as the product of the part of the mode in this layer and its absorption coefficient. The internal losses (α_i) are defined as sum of optical losses of all layers

$$\alpha_i = \sum_j \frac{\int_j |E(x)|^2\,\mathrm{d}x}{\int_{-\infty}^{+\infty}|E(x)|^2\,\mathrm{d}x}\alpha_j.$$

3. Results and discussion

In Fig. 1a we show a conventional laser structure emitting at 405 nm. It consists of 2 μm $\mathrm{Al}_{0.05}\mathrm{Ga}_{0.95}\mathrm{N}$:Si

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acting as n-type cladding layer, 100 nm GaN waveguide, an active region with three 3 nm $In_{0.12}Ga_{0.88}N$ quantum wells (QW) and 5 nm GaN quantum barriers (QB) followed by 20 nm of $Al_{0.15}Ga_{0.85}N{:}Mg^+$ acting as EBL and a 100 nm GaN:Mg waveguide. Above upper waveguide, 0.6 μm $Al_{0.05}Ga_{0.95}N{:}Mg$ p-type cladding layer and 60 nm $GaN{:}Mg^+$ heavily-doped contact layer are grown. The p-type contact is made from Ni/Au. The near-field distribution for the conventional structure is shown in Fig. 1b. One can see the optical mode confined around the active region with the highest refractive index.

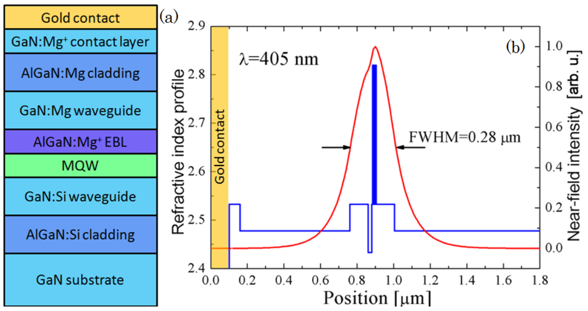

Fig. 1. (a) Conventional laser diode structure operating at $\lambda = 405$ nm, (b) corresponding refractive index profile and distribution of optical mode.

The optical mode distribution for the conventional laser structure have been calculated for three different wavelengths: 405 nm, 455 nm, 520 nm. Obtained confinement factors and full width at half maximum (FWHM) of near-field distribution are shown in Fig. 2. We see a striking drop of confinement factor with increasing wavelength which is correlated with increase in FWHM. As can be seen, the conventional LD structure does not provide sufficient Γ for true-blue and green lasers. To overcome this problem Lermer et al. [12] proposed using AlInN lattice-matched to GaN with a much lower refractive index as cladding layers. However, challenges in AlInN growth together with high activation energies of Si and Mg dopants make this proposition difficult for practical realization.

In order to compensate the drop of confinement factor for longer wavelengths we propose an alternative solution — to introduce a thick InGaN waveguide. We calculated the optical mode distribution for a structure similar to the conventional LD but containing additional InGaN waveguides from both sides of the active region as shown in Fig. 3a. Dependence of confinement factor on thickness of $In_{0.08}Ga_{0.92}N$ layers is shown in Fig. 3b for 455 nm and 520 nm. We found that for a structure lasing at 455 nm to provide the same confinement factor as for the conventional violet LD (dashed line in Fig. 3b) one has to use 2×55 nm of $In_{0.08}Ga_{0.92}N$. In case of LD lasing at 520 nm it is impossible to provide the same confinement factor with the use of InGaN waveguide of reasonable composition and thickness. To obtain $\Gamma = 0.9\%$ per QW for $\lambda = 520$ nm AlGaN claddings with higher Al content are required. We found that for 2×50 nm of $In_{0.15}Ga_{0.85}N$ waveguide AlGaN claddings with 10% of Al are sufficient to provide the same confinement factor as the conventional LD structure for $\lambda = 405$ nm.

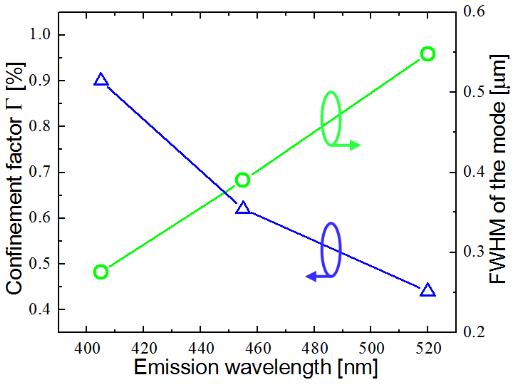

Fig. 2. Dependence of confinement factor and FWHM of near-field distribution on the wavelength for the conventional LD structure.

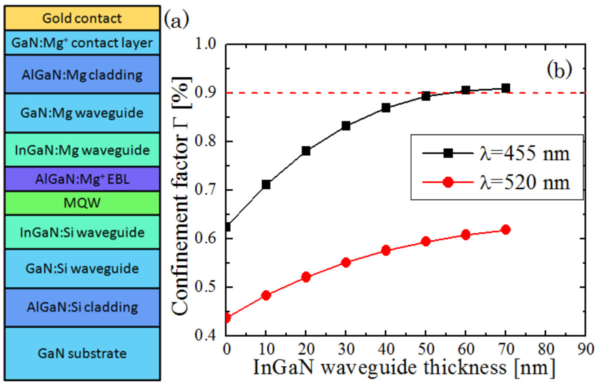

Fig. 3. (a) Laser structure with InGaN waveguides, (b) dependence of thickness of InGaN waveguide on confinement factor for blue and green LDs. The red dashed line indicates $\Gamma = 0.9\%$ for the conventional violet LD.

To link the confinement factor and optical losses with LDs parameters like threshold current density we consider the laser threshold condition given by

$$\Gamma g_{\mathrm{th}} = \alpha_i + \alpha_{\mathrm{m}},$$

where g_{th} is the threshold material gain, α_i and α_{m} are internal and mirror losses, respectively. By increasing Γ or by decreasing α_i one can reduce the threshold material gain which reduces the threshold current density for lasing.

To prove our theoretical findings we have grown two LDs (diode A and diode B) with different thickness of InGaN waveguide by PAMBE. Details of the growth and processing of these diodes can be found elsewhere [13]. Diode A consists of 2 μm $Al_{0.045}Ga_{0.955}N{:}Si$ cladding, 100 nm GaN waveguide, 40 nm of additional

$In_{0.08}Ga_{0.92}N$ waveguide, 3 nm $In_{0.17}Ga_{0.83}N$ single quantum well, 20 nm $In_{0.01}Al_{0.15}Ga_{0.84}N{:}Mg^+$ of EBL, 10 nm upper $In_{0.08}Ga_{0.92}N{:}Mg$ waveguide, 80 nm GaN waveguide, 250 nm of superlattice cladding with average composition of $Al_{0.075}Ga_{0.925}N{:}Mg$ followed by 100 nm of another superlattice cladding $In_{0.01}Al_{0.075}Ga_{0.915}N{:}Mg$. The last layer is a 20 nm $In_{0.01}Ga_{0.99}N{:}Mg^+$ contact layer. Diode B has a similar structure with three differences (i) 60 nm n-type GaN waveguide instead of 100 nm, (ii) 80 nm of $In_{0.08}Ga_{0.92}N$ waveguide instead of 40 nm, (iii) 350 nm of $Al_{0.075}Ga_{0.925}N$ superlattice cladding instead of 250 nm.

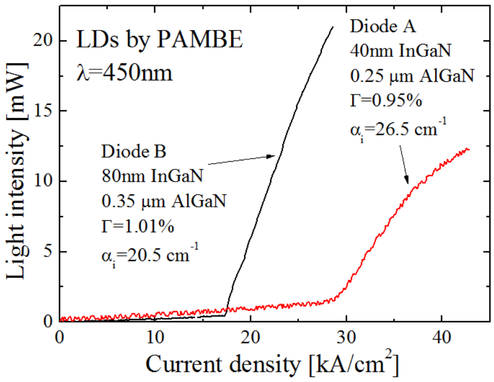

Fig. 4. *L–I* characteristics measured in pulsed mode with 200 ns pulse width and 0.1% duty cycle.

TABLE

Calculated confinement factor Γ, internal losses α_i and losses in metal contact α_{Au}.

Parameter	Diode A	Diode B
Γ [%]	0.95	1.01
α_i [cm^{-1}]	26.5	20.5
α_{Au} [cm^{-1}]	7.3	1.4

The *L–I* characteristics of these diodes are shown in Fig. 4. It is clearly seen that diode B with thicker InGaN waveguide and thicker AlGaN cladding has much lower threshold current and higher slope efficiency than diode A. In Table we present results of our calculations of Γ, α_i and optical losses in Ni/Au contact for these structures. For diode B we found that thicker InGaN waveguide increases Γ and lowers optical losses in p-type metal contact. To further decrease α_{Au} we have introduced thicker AlGaN cladding in diode B.

4. Conclusions

We studied the differences of optical mode parameters for violet, blue and green InGaN based laser diodes. We found a drop of confinement factor with increased light wavelength. We demonstrated that use of InGaN waveguides can compensate this decrease. We verified the theoretical predictions on two laser diodes grown by PAMBE with different waveguide design.

Acknowledgments

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