Index-antiguiding in narrow-ridge GaN-based laser diodes investigated by measurements of the current-dependent gain and index spectra and by self-consistent simulation

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Abstract: The threshold current density of narrow (1.5 µm) ridge-waveguide InGaN multi-quantum-well laser diodes, as well as the shape of their lateral far-field patterns, strongly depend on the etch depth of the ridge waveguide. Both effects can be attributed to strong index-antiguiding. A value of the antiguiding factor $R = 10$ is experimentally determined near threshold by measurements of the current-dependent gain and refractive index spectra. The device performances are simulated self-consistently solving the Schrödinger-Poisson equations and the equations for charge transport and waveguiding. Assuming a carrier-induced index change which matches the experimentally determined antiguiding factor, both the measured high threshold current and the shape of the far-field pattern of lasers with shallow ridges can be reproduced theoretically.

Index Terms: Diode Lasers, Gallium Nitride, Index-antiguiding, Index change, Lasing threshold, Simulation

I. INTRODUCTION

TODAY single-lateral-mode laser diodes emitting in the blue and violet regions of the spectrum find application in several fields, including optical data storage and spectroscopy, and are entering the market of laser projection [1,2]. In order to obtain stable emission by just one single lateral mode, it is essential that the shape and height of the ridge waveguide (RW) are chosen carefully [3,4]. In the (Al,Ga)N material system ridge widths of 2 µm or less are typically necessary to suppress the oscillation of higher-order modes [5].

It has been recently shown [6] that a small difference in the ridge etch depth of otherwise identical blue-emitting laser diodes can cause a large difference in the threshold current density. In order to explain such behavior, a simplified model based on strong antiguiding effects has been proposed [6]. By assuming a gain-independent antiguiding factor of 10 and step-like lateral distributions of the gain and the carrier-induced refractive index change in the multi-quantum well (MQW) structure, the large difference in threshold current could be reproduced. If the ridge is not deep enough, the carrier-induced index change can compensate the built-in refractive index step, causing radiation losses and an increase in the threshold current. The model was capable of reproducing the peculiar shape of the lateral far-field patterns of shallow-ridge devices where small side lobes appear on both sides of the main Gaussian peak. The side-lobes were attributed to the tilted phase-front of the mode due to antiguiding [7]. However, in the previous work, [6] the assumed high value ($R = 10$) of the antiguiding factor was not validated by measurements. Moreover, the step-like gain and refractive index model strongly simplified the real profiles.

In the present paper, after briefly introducing the devices under study, the antiguiding factor is determined by measurements of the current-dependent gain and index spectra. Realistic 2D electro-optical simulations of the laser diodes are then performed, and the results are compared to the experiment.

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II. Experimental Results

A. Device Fabrication and Characterization

The investigated InGaN multiple-quantum-well (MQW) RW laser diodes, emitting at about 440 nm, had a ridge width and a resonator length of 1.5 µm and 600 µm, respectively. Their facets were uncoated. The heterostructure, shown schematically in Fig. 1, consisted of an InGaN MQW active region sandwiched between step-graded InGaN/GaN waveguides and AlGaN cladding layers. The high-Al-content p-AlGaN electron blocking layer (EBL) was placed in the p-waveguide at the InGaN/GaN interface, 70 nm above the MQW. The depth of the active region, i.e. the vertical distance from the surface to the top quantum well (QW) was about 650 nm. Two sets of laser diodes were fabricated, which only differed in the etch depth of the ridge waveguide. The etch depths were 620 nm in the "deep-ridge" laser diodes and 450 nm in the "shallow-ridge" laser diodes. These values correspond to residual layer thicknesses above the MQW of $d_{RES,deep} = 30$ nm and $d_{RES,shallow} = 200$ nm, and built-in effective-index steps $\Delta n_{eff,deep} = 0.026$ and $\Delta n_{eff,shallow} = 0.004$ for the deep-ridge and the shallow-ridge devices, respectively. The thickness of each one of the four InGaN QWs was less than 4 nm, and the vertical confinement factor of the mode was $\Gamma = 0.038$ assuming a laterally infinite layer structure and neglecting the antiguiding effect. The epitaxial structure, including the real part of the refractive indices used in the simulations, is summarized in Table I. Further details on the structure and the fabrication process have been reported elsewhere [6], [8].

A large number of devices with uncoated facets were measured in pulsed operation (300 ns, 1 kHz), to avoid device heating. The threshold current ($I_{th}$) was between 90 mA and 110 mA for deep-ridge devices and between 220 mA and 330 mA for shallow-ridge devices. The scattering of the experimental values is attributed to spatial non-uniformities in the epitaxy and in the fabrication process. In Fig. 2, the $L-I$ characteristics and lateral (slow-axis) far-field patterns of representative devices are shown.

![Fig. 1. Schematic cross-section drawing of the fabricated devices.](image1)

![Fig. 2. Typical $L-I$ characteristics (a) and lateral far-field patterns [(b) and (c)] of deep-ridge and shallow-ridge devices. The facets are uncoated, and the emission measured from only one facet.](image2)
the excess carrier density, and \( \lambda \) is the wavelength. In the experiment, the modal differential gain and modal refractive index change are measured as function of current:

\[
R_{\text{exp}} = -\frac{4\pi}{\lambda} \frac{d n_{\text{MOD}}}{dI} \left( \frac{dI}{d n_{\text{MOD}}} \right). 
\]

(2)

where \( n_{\text{MOD}} \) is the modal index, \( g_{\text{MOD}} \) the modal gain, and \( I \) the current. The antiguiding factor \( R \) and the experimentally accessible value \( R_{\text{exp}} \) are equal as long as the optical confinement factor \( \Gamma \approx g_{\text{MOD}}/g \) is independent of the carrier density. This condition is assumed to be satisfied in the deep-ridge device. In the present section, the value of \( R_{\text{exp}} \) will be determined experimentally according to (2). In Section III the value of \( R \) necessary to theoretically reproduce the measurement data will be calculated and compared to \( R_{\text{exp}} \).

The wavelength-dependent differential modal gain, \( d g_{\text{MOD}}(\lambda)/dI \), was determined for the deep-ridge devices by the Hakki-Paoli method [10], [11]. From the modulation amplitude of the spectra of amplified spontaneous emission below threshold, the modal gain spectra \( g_{\text{MOD}}(\lambda) \) were obtained, as shown in Fig. 3(a). The measurement was performed in the current range 30 mA to 90 mA (in this specific device \( I_{\text{th}} = 90 \) mA), at intervals of 5 mA. The peak modal gain increases almost linearly with current, which translates into \( d g_{\text{MOD}}(\lambda)/dI = 0.7 \) cm\(^{-1}\)mA\(^{-1}\).

The differential modal index, \( d n_{\text{MOD}}/dI \), was derived from the spectral shift of the longitudinal modes between two consecutive current steps as described by Scheibenzuber et al. [12]. The obtained values are assumed to be the differential index change in the center of each 5 mA interval. Self-heating and the temperature-induced change of the modal index were avoided by keeping the waveguide temperature constant after determination of the thermal resistance [12]. The obtained \( d n_{\text{MOD}}/dI \) spectra are shown in Fig. 3(b).

From this data the value of the antiguiding factor at the peak wavelength of the modal gain spectra was determined, and is plotted in Fig. 3(c) as a function of current. The antiguiding factor is more than 50 at 30 mA and approaches a value of about 10 slightly below threshold. The value \( R_{\text{exp}} \approx 10 \) for the antiguiding factor at threshold is very large in comparison to other material systems [13], [14], but it is not untypical for InGaN MQW laser diodes [15].

![Fig. 3](image-url)

**III. Simulation Results and Discussion**

2D electro-optical simulations were performed with the software LASTIP by Crosslight Software Inc. [16]. The software solves self-consistently the Schrödinger equation, the Poisson equation, and the equations for charge transport and optical waveguiding; current spreading is taken into account as well. The hole mobility in the \( p \)-type layers was set to 10 cm\(^2\)V\(^{-1}\)s\(^{-1}\). Only half of the ridge was simulated due to the symmetry of the device. The lateral width of the simulated area was at
least 6 μm and perfectly matched layers (PMLs) were inserted at the boundaries. The imaginary part of the relative permittivity in the PMLs was 0.1, while their thickness was set to 6 μm. The thickness of the PMLs was chosen large enough to avoid unwanted reflections at the domain boundaries. The structure included the Pd contact metal, the SiNx insulating layer and the Ti contact pad. No substrate was taken into account. Only the real parts of the refractive indexes of the epitaxial layers were used. Optical absorption was taken into account by assuming a modal loss parameter $\alpha = 35 \text{ cm}^{-1}$, as determined by the Hakki-Paoli method [17]. The carrier-density-dependent part of the refractive index in the quantum wells was calculated by

$$\Delta n_{\text{dn}} = \frac{1}{2} \frac{dn}{dN} (n + p - n_0 - p_0),$$  \hspace{1cm} (3)

where $n$ and $p$ are the electron and hole densities under biased conditions, and $n_0$ and $p_0$ are the electron and hole densities at thermal equilibrium. Note that under lasing $n = N + n_0$ and $p = N + p_0$ hold in the quantum wells. The effect of the polarization charges at the interface boundaries was taken into account by using the model by Fiorentini et al. [17] and assuming 50% compensation by charged defects. The Poole-Frenkel field ionization of acceptors was also included. Considering the short current pulses used in the measurements, heating effects were neglected.

First, the threshold current of the deep-ridge device was adjusted to the experimental value by varying the parameter $C$ of the Auger recombination rate

$$R_{\text{Aug}} = C (n + p) (np - n_0 p_0).$$  \hspace{1cm} (4)

Assuming $C = 1.7 \times 10^{-30} \text{ cm}^6 \text{s}^{-1}$, $I_h = 100 \text{mA}$ was obtained, which corresponds nearly to the measured average threshold current of the deep-ridge laser diodes.

Next, the threshold current $I_h$ of the shallow-ridge laser diode was calculated using the same parameters. In contrast to the deep-ridge, $I_h$ of the shallow-ridge strongly depends on the antiguiding parameter. Using $\frac{dn}{dN} = -58 \times 10^{-22} \text{ cm}^3$, $I_h = 270 \text{mA}$ was obtained for the shallow-ridge device, which roughly agrees with the average experimental value. On the contrary, neglecting the antiguiding effect, $I_h$ for the shallow ridge was only slightly larger than for deep-ridge. The calculated $L$–$I$ curves are shown in Fig. 4 (a).

A comparable increase of the threshold current could be obtained by a hypothetical increase of the hole mobility in the p-doped layers from 10 to 500 cm$^2$/Vs, resulting in an increased current spreading effect. However, as discussed in Ref. [18], no experimental investigation could find any evidence of a significant difference in current spreading between the shallow-ridge and deep-ridge devices. Additionally, the side lobes visible in the measured far-field patterns were not obtained in the simulation. Figures 4 (b) and 4 (c) show the lateral far-field patterns for both devices calculated using the antiguiding coefficient reported above.

In the shallow-ridge case, side lobes are obtained which are very similar to the ones observed in experiment [compare Fig.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Calculated $L$–$I$ characteristics (a) and lateral far-field patterns (b) and (c) of the deep-ridge and shallow-ridge laser diodes assuming an antiguiding coefficient $dn/dN = -58 \times 10^{-22} \text{ cm}^3$. In (d) and (e) the mode intensity in the top QW is plotted as a function of the lateral distance from the ridge center $x$.}
\end{figure}
In Fig. 4 (d) and (e) the calculated lateral mode intensity distribution is shown: note that in the shallow-ridge case the mode is broader and has much longer tails, extending almost over the whole simulation domain, due to the weaker guiding. These tails are the origin of the side lobes visible in the far-field pattern.

The effect of the large antiguiding coefficient on the lateral mode confinement can be illustrated by considering the carrier-induced effective index change of the shallow-ridge laser diode as a function of $x$ after integration in transverse direction $y$, i.e.

$$
\Delta n_{\text{eff},x} (x) = \frac{\int_{-\infty}^{\infty} E(0, y)^2 \Delta n_{x,y}(x, y) dy}{\int_{-\infty}^{\infty} E(0, y)^2 dy}.
$$

(5)

The obtained effective index profile is shown in Fig. 5. In the center of the ridge ($x = 0$) the absolute value of the carrier-induced change of the effective index $|\Delta n_{\text{eff},y}(x)| = -0.0058$ is larger than the built-in index step $\Delta n_{\text{eff},\text{shallow}} = 0.004$. It can be therefore concluded that the lateral leakage of the optical mode due to index-antiguiding is responsible for the increased threshold current and the appearance of lateral side-lobes in the far-field pattern of shallow ridge lasers. Note that, not only the calculated carrier-induced change of the effective index of the deep-ridge laser $|\Delta n_{\text{eff},y}(x)| = -0.0043$ is smaller than the corresponding value of the shallow-ridge laser due to the much lower carrier density at threshold, but it is also much smaller than the built-in index step $\Delta n_{\text{eff,deep}} = 0.026$. It is interesting to note that the carrier-induced index depression in Fig. 5 extends over several micrometers beyond the ridge. This effect is due to the lateral spreading of the charge carriers, which is enhanced by increasing the drive current and the carrier density in the MQW.

In order to judge how far the value assumed for $dn/dN$ in the simulations is realistic, the corresponding antiguiding factor $R$ of the simulated deep-ridge laser diode was calculated. It is important to note that the assumption of a constant $dn/dN$ in the simulation is an approximation for real devices for which $dn/dN$ should change with the current. Therefore, the value of the antiguiding factor is only derived from the simulations at threshold. The values of $\lambda$, $dn_{\text{MOD}}/dI$, and $dg_{\text{MOD}}/dI$ were obtained as a function of the current from the simulations, and substituted in (2). At $I_{\text{th}} = 100$ mA, a value $R = 11.0$ was obtained. Considering the approximations, this number is in excellent agreement with the experimentally determined value of $R_{\text{exp}} = 10$. The values of $dn_{\text{MOD}}/dI$ and $R$ derived from the simulations are indicated by stars in Fig. 3(c).

IV. Conclusions

InGaN MQW RW laser diodes with two different ridge etch depths were investigated. A relatively small reduction in the etch depth (70 nm) resulted in a large increase in the threshold current density by a factor 2.5 to 3 as well as the appearance of side lobes in the lateral far-field patterns. Using the Hakki-Paoli method an antiguiding factor $R_{\text{exp}} = 10$ was determined experimentally, which should result in strong antiguiding effects. Self-consistent simulations show that, assuming a carrier-induced index change which is in agreement with the measured antiguiding factor, both the large threshold and the side-lobes in the far-field pattern can be reproduced.
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