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Semipolar III-Nitride laser diodes for solid-state lighting

Shlomo Mehari^{a,*}, Daniel A. Cohen^a, Daniel L. Becerra^a, Haojun Zhang^c, Claude Weisbuch^{a,b},
James S. Speck^a, Shuji Nakamura^{a,c}, and Steven P. DenBaars^{a,c}

^aMaterials Department, University of California, Santa Barbara, California 93106, USA

^bLaboratoire de Physique de la Matière Condensée, CNRS, Ecole Polytechnique, 91128 Palaiseau,
France,

^cElectrical and Computer Engineering Department, University of California, Santa Barbara,
California 93106, USA

ABSTRACT

Several hurdles to further enhance the performance of semipolar III-Nitride laser diodes are addressed in this work. Particularly, we focused on improving their high operating voltage by thinning the p-GaN cladding layer and utilizing a transparent conductive oxide p-contact. On-wafer optical absorption measurements showed that a further reduction in voltage with thinner p-GaN was limited by increased optical loss due to increased mode overlap with the ITO/metal anode. In separate attempts to minimize bulk-related optical losses, we implemented a new design that consisted of an AlGaIn electron blocking layer (EBL) placed remotely from the quantum wells (QWs) and a low p-waveguide Mg doping profile. A very low optical loss of about 2 cm^{-1} was extracted but the net improvement in differential efficiency was limited by lower internal injection efficiency due to carrier accumulation in the p-waveguide region. With an optimized design, that consisted of a lightly doped EBL close to the QWs and a UID p-waveguide, an improved light output power of 1.4 W at 1.5 A and a low threshold current density of 1.2 kA/cm^2 were obtained.

Keywords: laser diodes, III-Nitride, semiconductor lasers, transparent conductive oxides, optical loss, laser lighting

1. INTRODUCTION

III-Nitride laser diodes (LDs) are poised to become essential components in a broad range of applications such as in medical diagnostics, quantum technologies, and lighting systems.^{1–3} Specifically, in high-intensity white lighting systems, such as in automobile headlights and stage lighting, III-Nitride LDs offer much higher spatial brightness and no efficiency droop above threshold compared to LEDs.⁴ To realize most of these applications, however, the power conversion efficiency (PCE) of visible III-Nitride LDs, which is still far lower than that of other III-V LDs,⁵ must be further improved. Research efforts in recent years, primarily focused on improving the material quality of violet to blue *c*-plane LDs, have shown great progress.⁶ But at longer wavelengths the picture looks far less rosy. A promising route to improve the PCE, especially at longer wavelengths, is to grow the quantum wells (QWs) on non-*c*-plane directions, which is predicted to improve the radiative efficiency and gain.⁷ Among the most prominent advantages of QWs grown on non-basal directions are: high indium incorporation, reduced hole effective mass due to anisotropic strain, and increased electron-hole wavefunction overlap due to lower polarization-related electrical fields.⁸ To fully exploit this potential, it is crucial to thoroughly understand the underlying physical mechanisms that deteriorate the LD's operation. In this context, we present here our recent work on blue III-Nitride LDs grown on semipolar GaN substrates. We carefully examined and analyzed the main hurdles that impeded their performance, focusing on improving the continuous-wave (CW) operating voltage and reducing the high optical losses. We discuss first our effort to mitigate with the high operating voltage. The voltage was greatly reduced by thinning down the p-GaN cladding layer thickness and replacing the metallic contacts with a tin-doped indium oxide (ITO) p-contact. The limitations of this approach with regard to a tradeoff between low voltage and low optical loss are discussed. We then present results from LDs with very low optical losses ($\sim 2\text{ cm}^{-1}$) that were obtained by redesigning our p-side waveguide region. The effects of carrier accumulation and tradeoff with lower injection efficiency are discussed.

2. DEVICE FABRICATION

The epitaxial layers in this work were grown by metal organic chemical vapor deposition (MOCVD) on a free-standing semipolar $(20\bar{2}1)$ n-GaN substrate, provided by Mitsubishi Chemical Corporation. A schematic cross-section of our typical edge-emitting LDs is shown in Figure 1. For blue LDs the multiple quantum well (MQW) region was designed with two 3.5 nm $\text{In}_{0.18}\text{Ga}_{0.82}\text{N}$ quantum wells and a single 7 nm GaN barrier layer. An additional 20 nm UID GaN layer was incorporated on either side of the active region. The n-side and p-side waveguides consisted of a 65 nm $\text{In}_{0.07}\text{Ga}_{0.93}\text{N}$ layer compositionally graded to GaN over 10 nm at each side. Their Si and Mg doping levels were about $1 \times 10^{19} \text{ cm}^{-3}$, respectively. A 10 nm Mg-doped ($4 \times 10^{19} \text{ cm}^{-3}$) p- $\text{Al}_{0.28}\text{Ga}_{0.72}\text{N}$ layer was implemented as an electron blocking layer (EBL) between the active region and the p-side waveguide. To study the impact of p-cladding design on the operating voltage, the p-GaN cladding layer's thickness was varied and was capped with a 15 nm p+ GaN contact layer (Mg was ramped to $1 \times 10^{20} \text{ cm}^{-3}$).

The samples were then processed into an edge-emitting laser structure consisting of a tin-doped indium oxide (ITO) p-contact, as detailed in Ref. 9. LDs were tested under pulse and continuous-wave (CW) electrical injection. The pulsed electrical and luminescence characteristics were measured using a pulse width of 1 μsec with a repetition rate of 10 kHz. The light output power was measured by collecting the light emitted with a calibrated Si photodiode and integrating sphere.

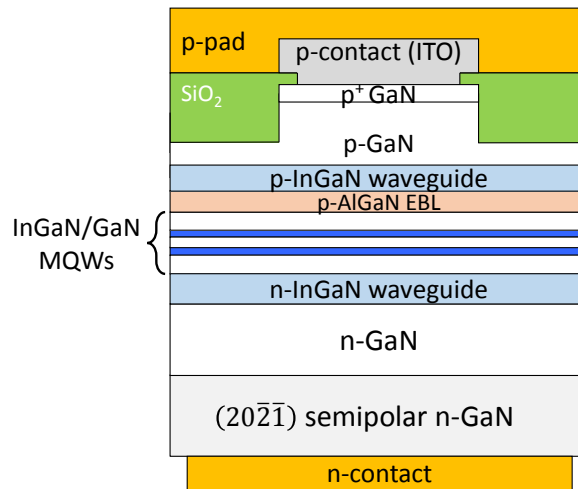


Figure 1. Schematic cross-section of an edge-emitting laser diode grown on a semipolar GaN substrate.

3. RESULTS AND DISCUSSION

3.1 Impact of p-GaN on LD's operating voltage

To reduce the operating voltage, we explored the impact of the p-side cladding design. Unlike in LEDs, the Mg doping levels in the p-GaN layer cannot be too high or else it would increase the optical loss. Instead, we thinned down the p-GaN thickness and replaced the metallic p-contact with a low absorption ITO contact. As shown in Figure 2a), when the p-GaN thickness was decreased from 650 nm to 250 nm the CW operating voltage significantly decreased from 7.2 V to 5.4 at 10 kA/cm^2 without impacting the light output characteristic (not shown here). A further reduction in the p-GaN thickness from 250 nm to 150 nm (with a different set of LDs that consisted of a lower n-side Si doping of $1 \times 10^{18} \text{ cm}^{-3}$) an additional decrease in the operating voltage was observed, as shown in the CW light-current-voltage (L - I - V) characteristics of $8 \times 1200 \mu\text{m}$ LDs (Figure 2b)). However, the light output power at this point started to deteriorate. Its peak intensity dropped from 1.7 W for 250 nm p-GaN to 1.5 W for 150 nm p-GaN. To better understand this tradeoff behavior, namely, degradation of the light output power with an improved operating voltage, we have studied the absorption spectra of these devices using the segmented contacts method.¹⁰ The aim was to identify differences in absorption losses due to a possible optical mode penetration into the ITO/metal contacts.

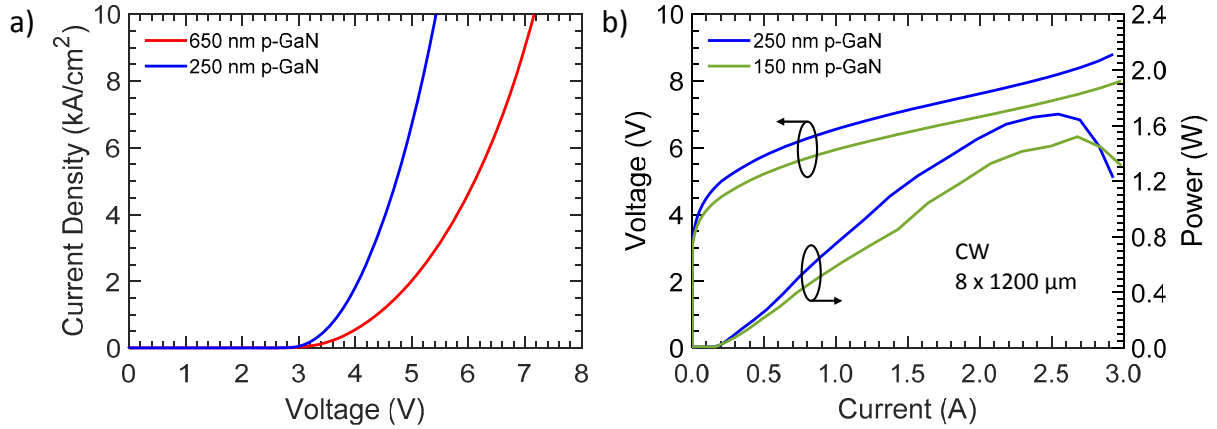


Figure 2. a) Current voltage characteristics of LD structures with p-GaN cladding layer thicknesses of 650 nm and 250 nm. b) CW L - I - V curves of $8 \times 1200 \mu\text{m}$ LDs with 250 nm and 150 nm p-GaN.

Figure 3 a) shows a schematic top-view illustration of the segmented contacts structure. Two segments of equal length ($L=300 \mu\text{m}$) were patterned. A front contact, closer to the output facet, and a back contact, away from the output facet were separated by a $3 \mu\text{m}$ gap. An $8 \mu\text{m}$ wide front facet (laterally angled by 11° to suppress feedback) was incorporated to emit amplified spontaneous emission (ASE). No rear facet was used, and an extended length of absorbing region insured there was no reflection from the back edge of the ridge. The light output was collected using a set of objective lenses and a single mode optical fiber connected to an array spectrometer. The absorption spectra were obtained using equation (1),¹⁰ assuming a uniform structure,

$$-\Gamma\alpha - \langle\alpha_i\rangle = \frac{1}{L} \ln \left(\frac{I_{meas}(back)}{I_{meas}(front)} \right), \quad (1)$$

where I_{meas} refers to the ASE intensity measured when a certain segment is injected (front or back), $\Gamma\alpha$ is the modal absorption (Γ and α are the confinement factor and the absorption coefficient of the gain medium, respectively), and $\langle\alpha_i\rangle$ is the internal optical modal loss.

The absorption spectra of the LDs with 250 nm and 150 nm p-GaN measured at 2 kA/cm^2 are compared in Figure 3 b). From the asymptotic value at long wavelengths of the absorption curves we find an increase in the optical loss from about 19 cm^{-1} for the LDs with 250 nm p-GaN to about 25 cm^{-1} for LDs with 150 nm p-GaN.

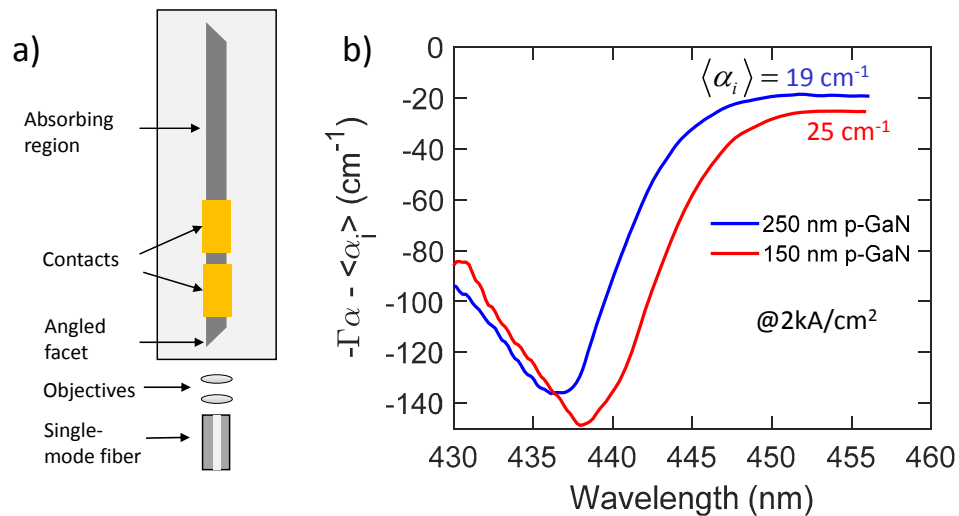


Figure 3. a) Top-view illustration of the segmented contacts structure and optical setup, b) absorption curves of LDs with a 250 nm and a 150 nm p-GaN thickness measured at 2 kA/cm^2 .

In an attempt to understand the contributions of the p-contact (about 200 nm ITO) and the top metallic p-pads (Ti/Au 30/1000 nm) to the increased optical loss, we carried out optical mode profile simulations for the LDs' structures with 250 nm and 150 nm p-GaN. Comparing the two calculated mode profiles, as shown in Figure 4, we find that the overlap with the ITO contact layer increased from 0.06% to 0.14% and the overlap with the metallic p-pads increased from 5×10^{-6} % to 5×10^{-4} % when the p-GaN thickness was decreased from 250 nm to 150 nm, respectively. These variations might seem low, but considering the relatively high absorption coefficient of these layers the optical loss differences can be well explained. Our standard un-annealed ITO contacts ($\text{In}_2\text{O}_3:\text{Sn}_2\text{O}_3$ 90:10%wt) have an absorption coefficient of $\sim 1700 \text{ cm}^{-1}$ (Figure 5, left red column), and the metallic p-pads absorption coefficient is in the range of $\sim 10^6 \text{ cm}^{-1}$, we thus estimated an increased loss of about 1.4 cm^{-1} in the ITO layer and about 5 cm^{-1} in the metallic p-pads, comparing the 250 nm and 150 nm p-GaN designs.

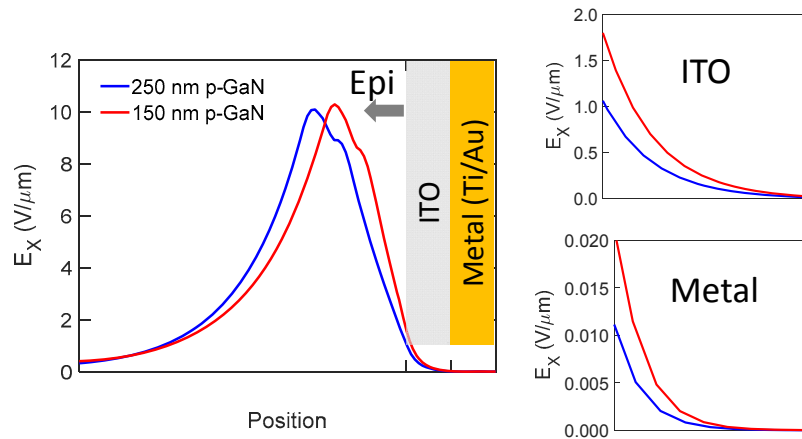


Figure 4. Comparison of the calculated optical mode profiles in LDs structures with a 250 nm and a 150 nm p-GaN thickness. The zoom-in figures (right side) show the increased overlap of the optical mode with the ITO contact and the metallic p-pads as the p-GaN thickness is reduced to 150 nm (distance scales on all graphs).

Obviously, a straightforward approach to mitigate this increased loss, if one wants to further reduce the operating voltage by further reducing the p-GaN thickness, is to increase the ITO thickness and reduce its absorption coefficient. One such approach we have explored to reduce the ITO's absorption coefficient is by changing its In_2O_3 to Sn_2O_3 weight ratio from our baseline ratio of 90:10 %wt to lower compositions. As shown in Figure 5, the absorption coefficient changed considerably with the tin %wt. With a 99.5:0.5 %wt ratio, the absorption coefficient decreased by an order of magnitude, while the resistivity increased only slightly (from $3.3 \times 10^{-4} \Omega\text{cm}$ to $6.4 \times 10^{-4} \Omega\text{cm}$). Since the transport in edge-emitting LDs is vertically this increased resistivity has no impact on the operating voltage. Further work is still required to incorporate this new contact schemes into a LD structure and test their contribution to a lower optical loss.

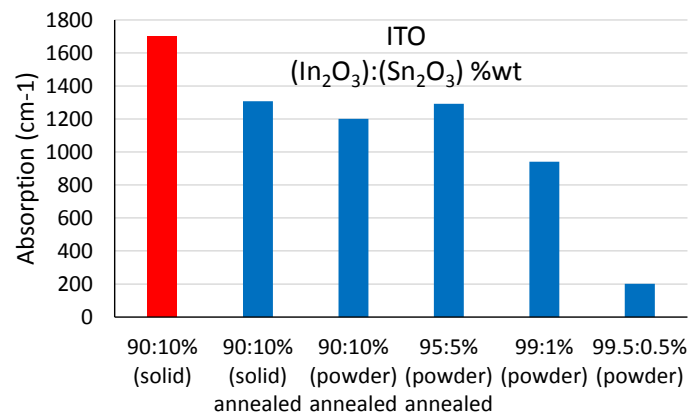


Figure 5. ITO's absorption coefficient as a function of its composition (In_2O_3 to Sn_2O_3 weight percentage). The left red column is our baseline solid composition of 90:10 %wt.

3.2 The role of p-waveguide design in LD's operation

In this section, we discuss the impact of the p-side waveguide design, particularly, its Mg doping profile and EBL location, on the LD's light output characteristics. Figure 6 a) shows the calculated optical mode profile along our standard LD structure together with the estimated optical losses in the different layers (shaded green). As a result of free-carrier absorption,¹¹ the highly Mg-doped regions, i.e., the p-AlGaIn and the p-InGaIn layers, contribute significant optical losses. To reduce these apparent high optical losses, we moved the EBL location remotely from the QWs (with slightly lower Mg doping levels) and also eliminated the Mg doping from the p-side InGaIn waveguide. A comparison between the Mg doping profile in our standard LD's structure and in the new design is shown in the secondary ion mass spectroscopy (SIMS) depth profiles in Figure 6 b). The peak Mg doping level was reduced from $4 \times 10^{19} \text{ cm}^{-3}$ to $8 \times 10^{18} \text{ cm}^{-3}$, and the InGaIn p-waveguide was changed to a UID doping level.

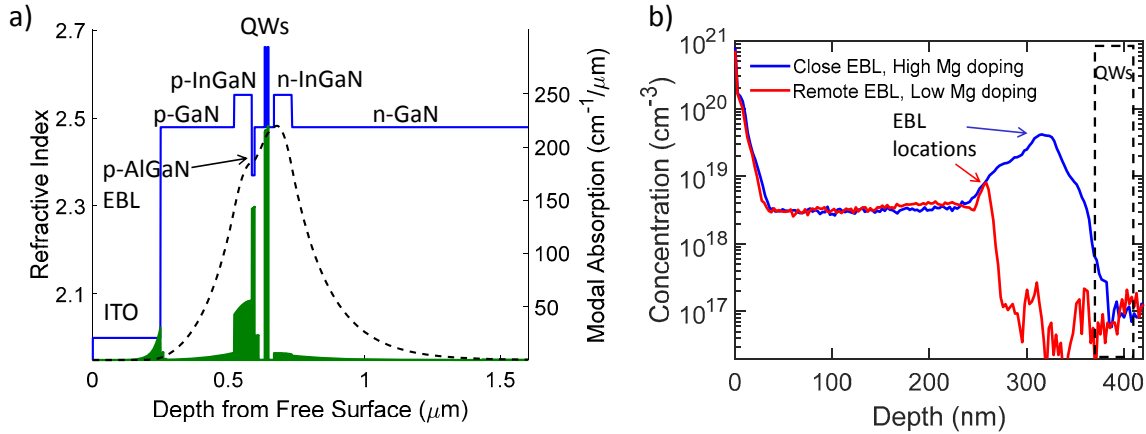


Figure 6. a) Optical mode profile calculation along our baseline LD layers with their associated optical loss (shaded green). b) Mg SIMS depth profile comparison between our baseline LD design, which consisted of a close EBL and high Mg levels, and our new LD design that consisted of a remote EBL and a UID InGaIn p-waveguide.

We processed LDs that had either a high Mg doping profile and EBL close to the QWs or a low Mg doping profile and a remote EBL. From the analysis of their absorption spectra, we find a significant reduction in the optical loss from about 20 cm^{-1} in the standard LD's design to about 2 cm^{-1} in the new design (Figure 7 a)). Despite this improvement in optical loss the net differential efficiency was fairly similar, as shown in the $L-I$ curves of these two designs in Figure 7 b). This is attributed to a reduction in injection efficiency: electrons escaping the quantum wells accumulate in the lower bandgap InGaIn waveguide, where they recombine with abundant holes traveling to the wells. The resulting carrier sink exacerbates electron leakage from the wells. The increase in threshold current density from 1.8 kA/cm^2 to 2.2 kA/cm^2 is consistent with this decrease in injection efficiency.

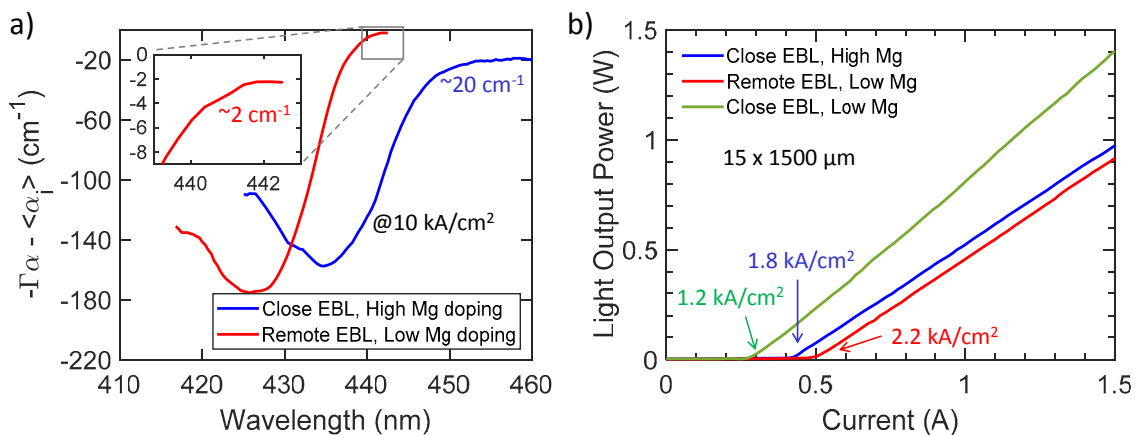


Figure 7. a) Absorption spectra of two LDs, one with an EBL close to the QWs and a high Mg doping profile, and a second with a remote EBL and a low Mg doping profile. b) $L-I$ curves of LDs with different p-WG designs.

In our latest attempt to suppress a possible carrier sink while still benefiting from lower optical losses, we also explored a LD design that consisted of a close EBL (with about half of Mg doping levels) and a UID InGa_N p-WG. As shown in Figure 7 b), with this design the threshold current density remarkably decreased to 1.2 kA/cm², indicating that the injection efficiency was improved. No reliable absorption spectra were taken yet for these LDs to estimate the impact on optical loss. But considering that the slope efficiency was also improved to 1.2 W/A, the optical losses are possibly lower than the standard LDs. Overall this optimized design enabled an increased light output power of 1.4 W at 1.5 A.

4. CONCLUSIONS

Several impediments to high power conversion efficiency in high power blue semipolar III-Nitride LDs were evaluated and addressed. The high CW operating voltage was found to decrease significantly with the thickness of the p-GaN cladding layer and further improvement was limited mainly by optical mode penetration into the metallic p-pads. A lower absorbing and thick ITO scheme might further improve the voltage. Optical losses were correlated with highly Mg doped regions and were optimized to enhance injection efficiency by suppressing carrier accumulation in the p-WG region. Further enhancement of the injection efficiency for the low optical loss LDs remains a challenge that needs to be addressed.

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REFERENCES

- [1] Najda, S. P., Perlin, P., Suski, T., Marona, L., Stanczyk, S., Wisniewski, P., Grzanka, S., Schiavon, D. and Leszczynski, M., "Ga_N laser diodes for quantum sensors, optical atomic clocks and systems," *Proc. SPIE* **10799**, 107990G-1 (2018).
- [2] Murayama, M., Nakayama, Y., Yamazaki, K., Hoshina, Y., Watanabe, H., Fuutagawa, N., Kawanishi, H., Uemura, T. and Narui, H., "Watt-Class Green (530 nm) and Blue (465 nm) Laser Diodes," *Phys. Status Solidi A* **215**(10), 1700513 (2018).
- [3] Masui, S., Nakatsu, Y., Kasahara, D. and Nagahama, S., "Recent improvement in nitride lasers," *Proc. SPIE* **10104**, 101041H (2017).
- [4] Pourhashemi, A., Farrell, R. M., Hardy, M. T., Hsu, P. S., Kelchner, K. M., Speck, J. S., DenBaars, S. P. and Nakamura, S., "Pulsed high-power AlGa_N-cladding-free blue laser diodes on semipolar (20-2-1) Ga_N substrates," *Appl. Phys. Lett.* **103**(15), 151112 (2013).
- [5] Crump, P., Erbert, G., Wenzel, H., Frevert, C., Schultz, C. M., Hasler, K.-H., Staske, R., Sumpf, B., Maassdorf, A., Bugge, F., Knigge, S. and Trankle, G., "Efficient High-Power Laser Diodes," *IEEE J. Sel. Top. Quantum Electron.* **19**(4), 1501211-1501211 (2013).
- [6] Kawaguchi, M., Imafuji, O., Nozaki, S., Hagino, H., Takigawa, S., Katayama, T. and Tanaka, T., "Optical-loss suppressed InGa_N laser diodes using undoped thick waveguide structure," *Proc. SPIE* **9748**, 974818 (2016).
- [7] Scheibenzuber, W. G., Schwarz, U. T., Veprek, R. G., Witzigmann, B. and Hangleiter, A., "Calculation of optical eigenmodes and gain in semipolar and nonpolar InGa_N/Ga_N laser diodes," *Phys. Rev. B* **80**(11), 115320 (2009).
- [8] Feezell, D. F., Speck, J. S., DenBaars, S. P. and Nakamura, S., "Semipolar (20-2-1) InGa_N/Ga_N Light-Emitting Diodes for High-Efficiency Solid-State Lighting," *J. Disp. Technol.* **9**(4), 190-198 (2013).
- [9] Mehari, S., Cohen, D. A., Becerra, D. L., Nakamura, S. and DenBaars, S. P., "Demonstration of enhanced continuous-wave operation of blue laser diodes on a semipolar (20-2-1) Ga_N substrate using indium-tin-oxide/thin-p-GaN cladding layers," *Opt. Express* **26**(2), 1564 (2018).
- [10] Blood, P., Lewis, G. M., Smowton, P. M., Summers, H., Thomson, J. and Lutti, J., "Characterization of Semiconductor Laser Gain Media by the Segmented Contact Method," *IEEE J. Sel. Top. Quantum Electron.* **9**(5), 1275-1282 (2003).
- [11] Kioupakis, E., Rinke, P., Schleife, A., Bechstedt, F. and Van de Walle, C. G., "Free-carrier absorption in nitrides from first principles," *Phys. Rev. B* **81**(24), 241201 (2010).