Performance enhancement of ultraviolet-C AlGaN laser diode

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Abstract The internal quantum efficiency (IQE) of deep ultraviolet (DUV) AlGaN-based laser diode (LD) emitting, in the wavelength region between 260 and 279 nm, is improved by proposing a quaternary-layer AlGaInN between the p-doped electron blocking layer (EBL) and the p-doped waveguide. This leads to an increase in the carrier concentration in the active region of the proposed LD. The radiative recombination rate is improved by 74% in the proposed LD. The current density is reduced from 21 kA/cm² (reference LD) to 6.13 kA/cm² (proposed LD). The proposed LD has a 71% higher internal quantum efficiency than the reference LD. Using SiLENSe™ 6.3, we analyzed both structures numerically.

1 Introduction

UV-emitting semiconductor optoelectronic devices are of tremendous interest for a wide range of applications, including solid-state lighting [1–3] and water sterilization [4–6]. In 2001, Nagahama et al. of Nichia Corporation developed the first single GaN quantum well UV laser diode [7]. Attention has recently been drawn to virus disinfection due to the prevailing COVID-19 pandemic. Thus, deep ultraviolet light-emitting devices have received quite some attention lately due to their microbial disinfection capabilities [8]. Some research organizations have been investigating UV-B and UV-C LDs lately. However, due to the low hole concentration in the p-doped cladding layer with large aluminum (Al) content, achieving high emission from the UV LD is a challenge [9]. The first electrically injected UV-C LD, with emission wavelength of 271.8 nm, has been reported [10]. As the operational wavelength of UV moves toward shorter wavelengths, Al-rich AlGaN layers are a necessity in the device fabrication. However, Al-rich AlGaN layers have several difficulties in in terms of maintaining highly crystallinity with optimized doping. This results in below par device performance. Other challenges that prevent improvement in UV LDs (ranging 200–280 nm) include the asymmetry in the electron/hole effective mass in III-Nitride LDs. Electron moves with high mobility in the active zone and thus leaks into p-region [11]. These leaked electrons may then recombine with the holes in the p-region, which will overcome the injection of holes in active region [12]. The recent proposed designs have overcome these challenges, which include the superlattice design of last quantum barrier [13], quaternary superlattice last barrier [14], double tapered EBL [15], step doping in waveguide and cladding layer [16], compositional Al-grading of silicon-doped layers [17], AlGaN-based polarization doped layers without impurity doping [18], step-graded quantum barriers with graded EBL [19] and inverse trapezoidal EBL [20].

In this work, we developed a high-efficiency AlGaN-based UV LD by incorporating a quaternary AlInGaN layer between p-EBL and p-waveguide. We discuss the effect of the quaternary layer on the performance of the proposed LD by evaluating different results like IQE, carrier concentration, electron and hole flux across the active zone, and radiative recombination rate as compared to the reference LD.

2 Structure and parameters

In this work, we employed reference LD (LD-A) as shown in Fig. 1, which consists of an n-Al0.69Ga0.31 N layer having a thickness of 100 nm and impurity doping of $1 \times 10^{18}$ cm$^{-3}$. A 700-nm-thick n-Al0.68Ga0.32 N cladding layer (CL) and an n-Al0.6Ga0.4 N waveguide layer (WGL) having a thickness of 30 nm are used. The active zone is comprised of four 3-nm-thick quantum wells (Al0.45Ga0.55 N) that are separated by five 8-nm-thick quantum barriers (Al0.55Ga0.45 N). The p-region consists of a 30-nm Al0.6Ga0.4 N waveguide layer (WGL) that provides good optical confinement. To prevent electron leakage, an electron blocking layer that is 20 nm thick with a 78% Al composition and a doping concentration of $5 \times 10^{20}$ cm$^{-3}$ is used. In addition, a 200-nm p-Al0.68Ga0.32 N (CL) and a 50-nm p-Al0.69Ga0.31 N layer are also employed. We added an extra 3-nm-thick quaternary layer with 70% aluminum, 20% gallium and 10% indium composition in our proposed UV-C LD-B as represented in Fig. 1. Both LDs have a cavity length of 1500 μm. Both end mirrors have a reflectance of 0.9. The design parameters are tabulated in Table 1. The following parameters were
Fig. 1 Structures of LD-A and LD-B

Table 1 Design parameters

| Design parameters | Values |
|--------------------|--------|
| Cavity length (microns) | 1500   |
| Stripe width (microns) | 2      |
| Back mirror reflectivity | 0.9    |
| Output mirror reflectivity | 0.5    |

used in the designs, i.e., electron and hole mobilities are 100 cm²V⁻¹ s⁻¹ and 10 cm²V⁻¹ s⁻¹, respectively, while the value of the Auger coefficient is 1 × 10⁻³⁰ cm⁶/s. We analyzed our structures numerically using SiLENSe™ 6.3. SiLENSe™ is a one-dimensional module that simulates the behavior of LD heterostructures made up of direct-bandgap wurtzite semiconductors like group-III nitrides and group-II oxides. It is based on a 1D drift–diffusion model that takes into account some of III-Nitride’s unique features such as direct-bandgap wurtzite semiconductor materials like TDD, low efficiency of acceptor activation, possible spontaneous electric polarization and piezoelectric polarization. The SiLENSe™ simulates the LD energy band diagrams as a function of voltage (bias), electron and hole momentum inside the LD heterostructure, and radiative and non-radiative recombination that causes light emission.

3 Theory and methodology

SiLENSe™ enables the user to design various layers of III-Nitride LDs by using bandgap engineering principles [21–23]. If \( J_n \) and \( J_p \) are the current densities of electrons and holes, respectively, then using the Golden Fermi’s rule, we can determine:

\[
J_n = q \mu_n n E + q D_n \nabla n \tag{1}
\]

\[
J_p = q \mu_p p E + q D_p \nabla p \tag{2}
\]

Electron and hole mobility are represented by \( \mu_n \) and \( \mu_p \), while carrier diffusion coefficients are denoted by \( D_n \) and \( D_p \). The relation of net current density \( J = J_n + J_p \) must follow the continuity equation:

\[
\nabla (J_n + J_p) + q \frac{\partial}{\partial t} (p - n) = 0 \tag{3}
\]

Also

\[
\nabla J_n - q \frac{\partial n}{\partial t} = +q R \tag{4}
\]

\[
\nabla J_p + q \frac{\partial p}{\partial t} = -q R \tag{5}
\]

The net recombination \( (R) \) is given as,

\[
R = R_n - G_n \quad \text{for electrons} \tag{6}
\]

\[
R = R_p - G_p \quad \text{for holes} \tag{7}
\]
The chemical rate equation of generation rate and recombination rate is given as,

\[ c_n + c_p \rightleftharpoons \gamma n + p \]

\[ R_n = R_p = c_n p G_n = G_p = e \]

The total recombination rate across an active region having width \( w \) is constant, then

\[ J_n = q w R = q w (R_n - G_n) \]

\[ J_p = q w R = q w (R_p - G_p) \]

From the absorption of each photon, an electron–hole pair is created. At an equilibrium, the net rate will be zero such as:

\[ R_n = c n_i p_i - e = 0 \]

\[ where \ e = c n_i p_i \]

hence the resultant recombination rate is then,

\[ R = c(n p - n_i p_i) \]

4 Results and discussion

At a current density of 10.7 kA/cm\(^2\) in Fig. 2a, LD-B has a higher internal quantum efficiency than LD-A. The maximum IQE of LD-A is 44%, whereas LD-B has a peak IQE of 73%. The efficiency droop is reduced from 50 to 5%. The emission spectra of both structures are represented in Fig. 2b. Figure 2b shows that at a current density of 10.7 kA/cm\(^2\), the emission peak of LD-B is higher than that of LD-A. Both LDs emit in the DUV range, i.e., 255–275 nm. The high intensity of LD-B is due to the high radiative recombination rate in the multiquantum wells which will be discussed further.

The IQE profile of varied thicknesses of the quaternary layer (QL) in LD-B is illustrated in Fig. 3a. The IQE reduces as the thickness of the QL increases from 3 to 8 nm. This is because a thick p-doped quaternary layer, i.e., 8 nm, results in limited hole transport toward the active region, lowering the radiative recombination rate and hence lowering the IQE. Thus, 3-nm thickness is the optimized thickness in the given device. Figure 3b depicts the IQE profile with different Al concentrations in QL. At 70% Al composition, the IQE is maximum with the lowest efficiency droop. IQE decreases as the Al content is increased further. LD-B with a 65% Al concentration in QL has a lower IQE than LD-B with a 70% Al content in QL. Similarly, LD-B with 80% Al content in QL has lower IQE as well as higher efficiency droop than LD-B with 70% Al content in QL. Thus, 70% aluminum is the optimized composition in the given device. The high Al concentration (80%) results in increased barrier height for holes due to which the hole injection in MQWs decreases. The number of electrons is high as compared to the number of holes, which results in the asymmetrical distribution of carriers in the active region. This reduces the device efficiency and increases the efficiency droop as shown in Fig. 3b. Similarly, low Al concentration (0.65) results in high electron leakage from the active zone that contributes to non-radiative recombination. The non-radiative recombination results in reduced IQE and power [24]. The optimum QL with 3 nm
thickness and 70% Al concentration reduces the lattice mismatch between the EBL and the active layers due to which the built-in polarization is reduced. The asymmetry between electrons and holes is minimized, which leads to a high radiative recombination rate. An optimized thickness and Al concentration in the quaternary layer are needed to enhance the IQE of the proposed device [25]. Thus, we have employed the optimized QL in LD-B.

The enhancement in IQE is due to optimum hole and electron concentration and their recombination in quantum wells (QWs). The electron and hole concentration profiles are shown in Fig. 4. It is found that the carrier concentration in the active region close to the p-side of the proposed LD-B is higher than the reference LD-A. The hole concentration is enhanced by 35% compared to LD-A as depicted in Fig. 4a. And the electron concentration is increased by 37%, as shown in Fig. 4b. Consequently, LD-B has a higher IQE than LD-A.

The high recombination rate in LD-B MQWs is responsible for the increase in IQE. The radiative recombination rate profiles of both LDs as a function of position are shown in Fig. 4c. LD-B has a higher rate of radiative recombination than LD-A. This is because many electrons and holes recombine in MQWs in LD-B. The presence of a p-doped quaternary layer between the p-EBL
Carrier current densities of LD-A and LD-B are plotted in Fig. 5. The electrons are injected into the active zone from the n-region and recombine with holes in quantum wells, resulting in a lower electron current density in the quantum well profile [26]. Also, because more carriers contribute to the radiative recombination rate, the drop in electron current density grows from n-region to p-region as illustrated in Fig. 5a. Electron leakage in LD-B is smaller than LD-A at the p-side of the last quantum well, indicating that more carriers recombined in quantum wells of LD-B. Similarly, the hole current density in LD-B is higher than in LD-A on p-side as illustrated in Fig. 5b.

Figure 6a illustrates the energy band profiles of LD-A and LD-B. The conduction band barrier height in LD-B is 335 meV, which is much larger than the barrier height of 297 meV in the reference LD-A as depicted in the figure. The increased barrier height prevents electron leakage on the p-side. The energy barrier height for holes in the valence band is reduced from 643 to 556 meV. So, the hole injection is larger in the active zone of the proposed LD (LD-B), which results in a high recombination rate.

The power (P) vs current (I) plot is depicted in Fig. 7. The threshold current of LD-A is about 662 mA, whereas the threshold current density of LD-A is 21 kA/cm². For LD-B, the threshold current is comparatively reduced to about 186 mA, whereas the threshold current density is 6.13 kA/cm². So, LD-B has a lower threshold current as compared to LD-A.

5 Conclusion

The influence of a quaternary layer on the optical performance of UV-C AlGaN-based laser diodes (LDs) is demonstrated in this study. The recombination of carriers increases in multiple quantum wells due to a 35% increase in hole concentration and a 37% increase in electron concentration, resulting in a 74% increase in the radiative recombination rate. The efficiency droop is reduced from 50% to 5%, and the IQE is improved by 73%. The emission intensity has greatly improved in our proposed LD-B. Therefore, our proposed LD-B could lead the researchers toward attaining high-efficiency AlGaN-based DUV LDs with little or no droop.
Fig. 7 P-I characteristics of LD-A and LD-B

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Data Availability Statement This manuscript has associated data in a data repository. [Authors’ comment: The data that support the findings of this study are available from the corresponding author upon reasonable request.]

Declarations

Conflict of interest The authors declare no conflicts of interest.

References

1. L. Wang, R.-J. Xie, T. Suehiro, T. Takeda, N. Hirosaki, Down-conversion nitride materials for solid state lighting: recent advances and perspectives. Chem. Rev. 118, 1951–2009 (2018)
2. A.I. Alhassan, N.G. Young, R.M. Farrell, C. Pynn, F. Wu, A.Y. Alyamani et al., Development of high performance green c-plane III-nitride light-emitting diodes. Opt. Express 26, 5591–5601 (2018)
3. C. Shen, J.A. Holguín-Lerma, A.A. Alatawi, P. Zou, N. Chi, T.K. Ng et al., Group-III-nitride superluminescent diodes for solid-state lighting and high-speed visible light communications. IEEE J. Sel. Top. Quantum Electron. 25, 1–10 (2019)
4. G. Matafonova, V. Batoev, Recent advances in application of UV light-emitting diodes for degrading organic pollutants in water through advanced oxidation processes: a review. Water Res. 132, 177–189 (2018)
5. S. Garcia-Segura, O.A. Arotiba, E. Brillas, The pathway towards photocatalytic water disinfection: review and prospects of a powerful sustainable tool. Catalysts 11, 921 (2021)
6. S. Gonca, B. Polat, Y. Ozay, S. Ozdemir, I. Kucukkara, H. Atmaca, et al., “Investigation of diode laser effect on the inactivation of selected Gram-negative bacteria, Gram-positive bacteria and yeast and its disinfection on wastewater and natural milk,” Environ. Technol., pp. 1–13, (2021).
7. S.-I. Nagahama, T. Yanamoto, M. Sano, T. Mukai, Ultraviolet GaN single quantum well laser diodes. Jpn. J. Appl. Phys. 40, L785 (2001)
8. I. Hadi, M. Dunowska, S. Wu, G. Brightwell, Control measures for sars-cov-2: A review on light-based inactivation of single-stranded rna viruses. Pathogens 9, 737 (2020)
9. D. Li, K. Jiang, X. Sun, C. Guo, AlGaN photonics: recent advances in materials and ultraviolet devices. Adv. Opt. Photonics 10, 43–110 (2018)
10. Z. Zhang, M. Kushimoto, T. Sakai, N. Sugiyama, L.J. Schowalter, C. Sasaoka et al., A 271.8 nm deep-ultraviolet laser diode for room temperature operation. Appl. Phys. Express 12, 124003 (2019)
11. Z. Ren, Y. Lu, H.-H. Yao, H. Sun, C.-H. Liao, J. Dai et al., III-nitride deep UV LED without electron blocking layer. IEEE Photonics J. 11, 1–11 (2019)
12. S. Shervin, S.K. Oh, H.J. Park, K.-H. Lee, M. Asadrad, S.-H. Kim et al., Flexible deep-ultraviolet light-emitting diodes for significant improvement of quantum efficiencies by external bending. J. Phys. D Appl. Phys. 51, 105105 (2018)
13. M. Amiriroseini, G. Alahyarizadeh, Enhancement of deep violet InGaN double quantum wells laser diodes performance characteristics using superlattice last quantum barrier. J. Optoelectr. Nanostruct. 6, 107–120 (2021)
14. G. Alahyarizadeh, M. Amiriroseini, M. Khorsandi, Performance enhancement of deep violet InGaN double quantum wells laser diodes with quaternary superlattice barriers structure. J. Renew. Energy Environ. 9, 106–111 (2022)
15. Y.-F. Wang, M.I. Niass, F. Wang, Y.-H. Liu, Reduction of electron leakage in a deep ultraviolet nitride laser diode with a double-tapered electron blocking layer. Chin. Phys. Lett. 36, 057301 (2019)
16. S. U. Khan, S. M. Nawaz, M.I. Niass, F. Wang, Y. Liu, Effects of the stepped-doped lower waveguide and a doped p-cladding layer on AlGaN-based deep-ultraviolet laser diodes, J. Russian Laser Res., pp. 1–8, (2022)
17. M.N. Sharif, M.A. Khan, Q. Wali, I. Demir, F. Wang, Y. Liu, Performance enhancement of AlGaN deep-ultraviolet laser diode using compositional Al-grading of Si-doped layers. Opt. Laser Technol. 152, 108156 (2022)
18. Z. Zhang, M. Kushimoto, M. Horita, N. Sugiyama, L.J. Schowalter, C. Sasaoka et al., Space charge profile study of AlGaN-based p-type distributed polarization doped claddings without impurity doping for UV-C laser diodes. Appl. Phys. Lett. 117, 152104 (2020)
19. Y.-F. Wang, M.I. Niass, F. Wang, Y.-H. Liu, Improvement of radiative recombination rate in deep ultraviolet laser diodes with step-like quantum barrier and aluminum-content graded electron blocking layer. Chin. Phys. B 29, 017301 (2020)
20. Z.-Q. Xing, Y.-J. Zhou, Y.-H. Liu, F. Wang, Reduction of electron leakage of AlGaN-based deep ultraviolet laser diodes using an inverse-trapezoidal electron blocking layer. Chin. Phys. Lett. 37, 027302 (2020)
21. D.-P. Nguyen, N. Regnault, R. Ferreira, G. Bastard, Alloy effects in Ga1–xInxN/GaN heterostructures. Solid State Commun. 130, 751–754 (2004)
22. K. Sato, S. Yasue, Y. Ogino, M. Iwaya, T. Takeuchi, S. Kamiyama et al., Analysis of spontaneous subpeak emission from the guide layers of the ultraviolet-B laser diode structure containing composition-graded p-AlGaN cladding layers. Physica Status Solidi (a) 217, 1900864 (2020)
23. K. Sato, T. Omori, K. Yamada, S. Tanaka, S. Ishizuka, S. Teramura et al., Analysis of carrier injection efficiency of AlGaN UV-B laser diodes based on the relationship between threshold current density and cavity length. Jpn. J. Appl. Phys. 60, 074002 (2021)
24. T. Wernicke, L. Sulmoni, C. Kuhn, G. Tränkle, M. Weyers, M. Kneissl, *Group III-Nitride-Based UV Laser Diodes*, in *Semiconductor Nanophotonics*, ed: Springer, 2020, pp. 505–548
25. A.J. Ghazai, S. Thahab, H.A. Hassan, Z. Hassan, Quaternary ultraviolet AlInGaN MQW laser diode performance using quaternary AlInGaN electron blocking layer. Opt. Express 19, 9245–9254 (2011)
26. J. Piprek, R. K. Sink, M. A. Hansen, J. E. Bowers, S. P. DenBaars, Simulation and optimization of 420-nm InGaN/GaN laser diodes, in Physics and Simulation of Optoelectronic Devices VIII, 2000, pp. 28–39