OPTIMIZATION OF AlGaN-BASED DEEP ULTRAVIOLET LASER DIODES WITH GRADED RECTANGULAR SUPERLATTICE ELECTRON BLOCKING LAYER AND GRADED TRAPEZOIDAL SUPERLATTICE HOLE BLOCKING LAYER

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Abstract

To improve the carrier confinement capability and optimize the performance of deep ultraviolet laser diodes (DUV-LDs), we propose the graded rectangular superlattice (GRSL) electron blocking layer (EBL) and the graded trapezoidal superlattice (GTSL) hole blocking layer (HBL) in this paper. Crosslight software is used to simulate and compare the DUV-LDs with rectangular superlattice (RSL) EBL and RSL HBL, GRSL EBL and GRSL HBL, and GRSL EBL and GTSL HBL. The simulation results indicate that GRSL EBL and GTSL HBL increase the carrier concentration in the quantum wells, reduce the electron leakage in the p-type region and the hole leakage in the n-type region, increase the radiation recombination rate, reduce the threshold voltage and threshold current, and increase the electro-optical conversion efficiency and output power of DUV-LDs more effectively.

Keywords: electron blocking layer, hole blocking layer, superlattice, carrier confinement.

1. Introduction

With the rapid development of semiconductor laser technology, semiconductor light-emitting devices have a wider application prospect in the deep ultraviolet band, such as the pollution prevention, surface disinfection, environmental protection, biomedical research, and high-density optical information storage [1–7]. Recently, the large-scale spread of the COVID-19 virus has aroused people’s attention to disinfection products. As a widely used disinfection product, the deep ultraviolet light-emitting device could be further developed [8]. Deep ultraviolet laser diodes (DUV-LDs) have the advantages of small size, lightweight, high conversion efficiency, high reliability, and easy light source assembly [9–11]. However, due to the high dislocation density in AlGaN materials, spontaneous and piezoelectric polarization

Manuscript submitted by the authors in English on March 15, 2022.

1071-2836/22/4304-0489©2022 Springer Nature Switzerland AG 489
field effects, and weak carrier confinement, DUV-LDs with wavelengths less than 280 nm still have the problems of low hole concentration, serious carrier leakage, and low radiation recombination rate and output power [12–14]. The use of electron blocking layer (EBL) and hole blocking layer (HBL) can reduce carrier leakage, increase recombination rate, and optimize the performance of devices [15]. To solve the above problems, Xing et al. proposed inverted trapezoidal EBL to reduce the electron leakage in the p-type region [16], Wang et al. proposed graded EBL to improve the radiative recombination rate in the quantum wells (QWs) of DUV-LDs [17], and Yi et al. proposed the specially designed AlGaN superlattice EBL and HBL based on rectangular superlattice (RSL) EBL and HBL [18]; then, they design AlGaN graded superlattice EBL and HBL to improve the performance of UV light-emitting diodes [19]. Though the use of the superlattice structure has achieved progress, there is still room for improvement.

To improve the carrier confinement capability and optimize the performance of DUV-LDs, we propose in this paper graded rectangular superlattice (GRSL) EBL and graded trapezoidal superlattice (GTSL) HBL. The DUV-LDs are simulated and compared with RSL EBL and RSL HBL, GRSL EBL and GRSL HBL, and GSRL EBL and GTSL HBL, respectively. The simulation results show that GRSL EBL and GTSL HBL have a significant effect on increasing carrier concentration in the quantum wells (QWs). They can reduce the electron leakage in the p-type region and hole leakage in the n-type region, increase the radiation recombination rate, reduce the threshold voltage and threshold current, and improve the electro-optical conversion efficiency and output power of DUV-LDs. The use of GRSL EBL and GTSL HBL can improve the carrier confinement capability and optimize the performance of DUV-LDs effectively.

2. Simulation Structure and Parameters

In Fig. 1a, we show the structure of the DUV-LD with 0.1 μm thick Al0.75Ga0.25N as the substrate. The n-type region is composed of a 1 μm thick Al0.75Ga0.25N cladding layer (n-doping = 5 \cdot 10^{18} \, \text{cm}^{-3}), a 0.11 μm thick Al0.68Ga0.32N lower waveguide layer (LWG) (n-doping = 5 \cdot 10^{19} \, \text{cm}^{-3}), and a 14 nm thick 3-period Al0.88Ga0.12N/Al0.84Ga0.16N RSL HBL (n-doping = 5 \cdot 10^{18} \, \text{cm}^{-3}). The active region consists of three 8 nm thick Al0.68Ga0.32N quantum barriers and two 3 nm thick Al0.58Ga0.42N quantum wells alternately. The p-type region consists of 14 nm thick 3-period Al0.94Ga0.06N/Al0.96Ga0.10N RSL EBL.

![Fig. 1. The epitaxial layer structures of the DUV-LD (a), RSL EBL (b), and RSL HBL (c).](image-url)
(p-doping $= 5 \cdot 10^{18} \text{ cm}^{-3}$), a 0.07 μm thick Al$_{0.08}$Ga$_{0.32}$N upper waveguide layer (UWG) (p-doping $= 5 \cdot 10^{19} \text{ cm}^{-3}$), a 0.4 μm thick Al$_{0.75}$Ga$_{0.25}$N cladding layer (p-doping $= 5 \cdot 10^{18} \text{ cm}^{-3}$), and a 0.1 μm thick Al$_{0.80}$Ga$_{0.20}$N contacting layer (p-doping $= 5 \cdot 10^{19} \text{ cm}^{-3}$). In this paper, we denote this structure as Structure A. The epitaxial layer structures of RSL EBL and RSL HBL are shown in Fig. 1 b and c, respectively.

On the premise that the thickness and average aluminum composition of EBL and HBL are the same, we design in this paper the DUV-LD with GRSL EBL and GRSL HBL (denoted as Structure B) and the DUV-LD with GRSL EBL and GTSL HBL (denoted as Structure C). GRSL EBL is composed of 3-period $p$-Al$_x$Ga$_{1-x}$N/Al$_{0.90}$Ga$_{0.10}$N SL ($x_1$, $x_2$, and $x_3$ are 0.92, 0.94, and 0.96, respectively); GRSL HBL is composed of 3-period $n$-Al$_x$Ga$_{1-x}$N/Al$_{0.84}$Ga$_{0.16}$N SL ($x_1$, $x_2$, and $x_3$ are 0.90, 0.88, and 0.86, respectively); GTSL HBL is composed of 3-period $n$-Al$_x$Ga$_{1-x}$N/Al$_{0.84}$Ga$_{0.16}$N SL ($x_1$ decreases from 0.91 to 0.89, $x_2$ decreases from 0.89 to 0.87, and $x_3$ decreases from 0.87 to 0.85). In Fig. 2, we show the changes in the aluminum composition of the EBL and HBL of the three structures. The Crosslight software is used to simulate the DUV-LDs with RSL EBL and RSL HBL, GRSL EBL and GRSL HBL, and GRSL EBL and GTSL HBL. During the simulations, the cavity length and width of DUV-LDs are set to 530 and 4 μm, respectively, and the reflectivity of the front and rear mirrors is set to 30% [20]. The built-in interface charge caused by the spontaneous and piezoelectric polarizations is calculated at 40% of the theoretical value [21]. In addition, the ambient temperature is set to 300 K.

3. Results and Discussion

The energy band affects the migration and distribution of carriers and further influences the performance of the device [22]. Therefore, it is important to study the changes in the energy band. Due to the polarization electric field effect, the EBLs and HBLs of different structures have different effective barrier heights [23]. The effective barrier height is defined as the potential difference between the energy band edge and its corresponding quasi-Fermi level [24], and it has a certain influence on the injection and confinement of carriers. In Fig. 3, we show the energy band and quasi-Fermi level of Structure A (a), Structure B (b), and Structure C (c), respectively. For EBLs, the effective barrier heights of the electrons in the conduction band of Structure A, Structure B, and Structure C are 668, 714, and 716 meV, respec-
respectively, and the effective barrier heights of the holes in the valence band of three structures are 120, 112, and 108 meV, respectively. Compared with Structure A and Structure B, the effective barrier height of the electrons in Structure C is increased by 48 and 2 meV, respectively, and the effective barrier height of holes is reduced by 12 and 4 meV, respectively. For HBLs, the effective barrier heights of electrons in the conduction band of the three structures are 247, 210, and 199 meV, respectively, and the effective barrier heights of the holes in the valence band of the three structures are 241, 298, and 418 meV, respectively. Compared with Structure A and Structure B, the effective barrier height of the electrons in Structure C is reduced by 48 and 11 meV, respectively, and the effective barrier height of the holes is increased by 177 and 120 meV, respectively. One can see from these comparison that Structure C has a higher effective barrier height to prevent the carrier leakage and a lower effective barrier height to facilitate the carrier injection, which implies the improvement in the carrier confinement capability.

![Fig. 3. Energy band diagrams of Structure A (a), Structure B (b), and Structure C (c). Here, the energy bands are shown by solid curves and the quasi-Fermi levels are shown by dashed curves.](image)

The carrier confinement capability can be explained intuitively by the carrier concentration in the QWs and the carrier leakage in the nonactive region. During the operation of the device, holes recombine with electrons in the QWs, and a higher carrier concentration will lead to higher recombination efficiency. Meanwhile, there will be a large number of carriers that have not recombined with each other successfully [25]. The carriers escaping from QWs leak into the $p$-type and $n$-type regions, which will negatively affect the performance of the device [26]. Therefore, higher carrier injection and lower carrier leakage mean better carrier confinement capability and performance of devices [27]. In Fig. 4, we show the electron concentration in the QWs (a), the hole concentration in the QWs (b), the electron leakage in the $p$-type region (c), and the hole leakage in the $n$-type region (d), respectively. Compared with Structure A and Structure B, Structure C has higher electron and hole concentrations in the QWs. Quantitative analysis shows that compared with Structure A, the electron leakage of Structure C is reduced by 4.04%, and compared with Structure A and Structure B, the hole leakage of Structure C is reduced by 13.34% and 11.38%, respectively. These results show that among the three structures, Structure C has the highest carrier concentration in the QWs and the lowest carrier leakage in the $p$-type and $n$-type regions, which means that GRSL EBL and GTSL HBL can improve the carrier confinement capability more effectively.

The recombination rate is significantly affected by the carrier concentration in the QWs [28]. In the operating process of DUV-LDs, the probability of carrier recombination will increase with increase in the carrier concentration in the QWs [29]. Radiation recombination is the recombination of electrons...
Fig. 4. The electron concentration in the QWs (a), the hole concentration in the QWs (b), the electron leakage in the $p$-type region (c), and the hole leakage in the $n$-type region (d). Here, dotted curves are for Structure A, dashed curves are for Structure B, and solid curves are for Structure C.

and holes in QWs, and the energy is released in the form of photons [30], which is the luminescence mechanism of DUV-LDs. Therefore, the radiation recombination rate is a crucial parameter for DUV-LDs. In Fig. 5a, we show the comparison of the radiation recombination rates of the three structures under study. Compared with Structure A and Structure B, the radiation recombination rate of Structure C is increased by 4.11% and 1.76%, respectively. Combined with the previous explanation, the reason for the increased radiative recombination rate is that the use of GRSL EBL and GTSL HBL increases the carrier concentration in the QWs.

Improved carrier confinement capability can also be reflected by decrease of the threshold voltage [31]. In Fig. 5b, we show the $I$–$V$ curves of the three structures. According to the simulation results, the threshold voltages of the three structures are 4.86, 4.82, and 4.74 V, and the resistances are 3.41 Ω, 3.39 Ω, and 3.03 Ω, respectively. Compared with Structure A and Structure B, the threshold voltage of Structure C is reduced by 2.47% and 1.66%, respectively, and the resistance is reduced by 11.14% and 10.62%, respectively. The results show that GRSL EBL and GTSL HBL can reduce the threshold voltage and the resistance of DUV-LDs more effectively. Under the same conditions, the lower the
threshold voltage of the devices, the higher injection current they will obtain; the smaller resistance of the devices, the smaller heat loss they will generate. This indicates that the reduction of threshold voltage and resistance has a positive effect on the improvement of the electro-optical conversion efficiency of DUV-LDs.

The electro-optical conversion efficiency is defined as the ratio between the output optical power and the input electrical power [32]. In Fig. 6a, we show the electro-optical conversion efficiency of the three structures under study. The electro-optical conversion efficiency values under the same current of the three structures are taken for quantitative analysis. Compared with Structure A and Structure B, the electro-optical conversion efficiency of Structure C is increased by 11.68% and 5.67%, respectively. The improvement of the electro-optical conversion efficiency of DUV-LDs with GRSL EBL and GTSL HBL shows lower energy consumption and smaller heat dissipation cost.

Fig. 5. The radiative recombination rate (RRR) in the QWs (a) and the \( I-V \) curves of three structures (b). Here, dotted curves are for Structure A, dashed curves are for Structure B, and solid curves are for Structure C.

Fig. 6. The electro-optical conversion efficiency of three structures (a) and the \( P-I \) curves of three structures (b). Here, dotted curves are for Structure A, dashed curves are for Structure B, and solid curves are for Structure C.
The threshold current is the forward current value when the laser diodes are converted from the spontaneous radiation to the stimulated radiation. We show that the reduction of threshold current can increase the light output power of the device and optimize the performance of devices [33]. In Fig. 6b, we show the $P$–$I$ curves of the three structures. The threshold currents of the three structures are 32.23, 31.85, and 30.82 mA, respectively. Compared with Structure A and Structure B, the threshold current of Structure C is reduced by 4.37% and 3.23%, respectively. The slope efficiency shows the ability of the output power to increase with the current. Based on the simulation results, the slope efficiency of the three structures is calculated; they are 1.44, 1.57, and 1.73, respectively. Compared with Structure A and Structure B, the slope efficiency of Structure C is increased by 20.14% and 10.19%, respectively. Lower threshold current and higher slope efficiency have a positive impact on the improvement of output power. The output power of DUV-LDs also plays a vital role in the performance of DUV-LDs. Higher output power means better performance. According to the simulation result shown in Fig. 6b, when the current is 95 mA, the output powers of the three structures are 95.65, 103.07, and 110.74 mW, respectively. Compared with Structure A and Structure B, the output power of Structure C is increased by 15.78% and 7.44%, respectively. The results show that GRSL EBL and GTSL HBL improve the output power of DUV-LDs more effectively.

4. Conclusions

In this paper, we proposed the GRSL EBL and the GTSL HBL to improve the carrier confinement and optimize the performance of DUV-LDs. AlGaN-based DUV-LDs with RSL EBL and RSL HBL, GRSL EBL and GRSL HBL, and GRSL EBL and GTSL HBL were simulated and compared, respectively. The results obtained show that GRSL EBL and GTSL HBL can increase the carrier concentration in the QWs and reduce the electron leakage in the $p$-type region and the hole leakage in the $n$-type region, indicating that the use of them can significantly improve the confinement capability. The quantitative analysis showed that the radiation recombination rate was greatly improved, and the threshold voltage and resistance were reduced to 4.74 V and 3.03 Ω, respectively. Meanwhile, with the improvement of the radiative recombination rate and the reduction of heat loss, the electro-optical conversion efficiency was increased to 37.3%. In addition, as the threshold current was reduced to 30.82 mA and the slope efficiency was increased to 1.73, the output power was increased to 110.74 mW. In summary, the use of GRSL EBL and GTSL HBL can effectively improve the carrier confinement capability and the radiative recombination rate in the QWs, which helps to reduce the threshold voltage and resistance and improve the electro-optical conversion efficiency and output power of DUV-LDs. The study results provide a valuable reference for optimizing the optical and electrical properties of DUV-LDs by improving the carrier confinement capability.

Acknowledgments

This work was supported in part by the Special Project for Inter-Government Collaboration of State Key Research and Development Program under Grant No. 2016YFE0118400, Zhengzhou 1125 Innovation Project under Grant ZZ2018-45, Ningbo 2025 Key Innovation Project under Grant No. 2019B10129, and the National Natural Science Foundation of China Henan Provincial Joint Fund Key Project under Grant No. U1604263.
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