JREE: Vol. 9, No. 1, (Winter 2022) 106-111

Journal of Renewable Energy and Environment

Journal Homepage: www.jree.ir

Materials and Energy Research Center

MERC

Research Article

Performance Enhancement of Deep Violet InGaN Double Quantum Wells Laser Diodes with Quaternary Superlattice Barriers Structure

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PAPER INFO

Paper history:
Received: 07 September 2021
Revised in revised form: 31 October 2021
Scientific Accepted: 14 November 2021
Published: 11 January 2022

Keywords:
InGaN Quantum Well Laser,
Superlattice Barriers,
Electrical and Optical Properties,
Numerical Simulation

ABSTRACT

The performance characteristics of InGaN Double-Quantum-Well (DQW) Laser Diodes (LDs) with different barrier structures were studied numerically by Integrated System Engineering Technical Computer-Aided Design (ISE TCAD) software. Three different kinds of structures of barriers including quaternary AlInGaN and AlInGaN/AlGaN superlattice barriers were used and compared with conventional GaN in InGaN-based laser diodes. Replacing the traditional GaN barriers with quaternary AlInGaN increased holes and electrons flowing in the active region and thus, the radiative recombination enhanced the output power. However, it did not reduce the threshold current due to hole and electron overflowing. To investigate the ways of greatly reducing the threshold current, the structure consisting of AlInGaN/AlGaN superlattice barriers was proposed. The simulation showed that electrical and optical characteristics such as output power, Differential Quantum Efficiency (DQE), and slop efficiency were significantly enhanced for LDs containing superlattice barriers compared to the basic structure. This is while the threshold current was considerably reduced. The enhancement was mainly attributed to the improvement of hole injection and also the blocking hole and electron overflowing caused by the reduction of polarization charges at the interface between the barriers, the well, and the Electron Blocking Layer (EBL).

https://doi.org/10.30501/jree.2021.300112.1246

1. INTRODUCTION

III-Nitride materials present unique physical properties such as wide, direct, and tunable bandgap energy, high electron mobility, saturation velocity, coverage of the electromagnetic spectrum, high thermal stability, and high absorption coefficient which made them the best candidate materials for optoelectronics applications including LD, LED, and solar cells. III-Nitride family laser diodes have recently made significant progress in a wide range of applications such as full-color displays, lighting systems, optical storage, chemical sensors, printing, and medical applications [1-3]. GaN-based semiconductor lasers are now commercialized. However, researchers are trying to reach laser diodes with shorter emission wavelengths and excellent performance for the next generation of laser sources. They provide a safer condition for various applications including high-density optical disc systems [4, 5]. Nevertheless, LDs structures enjoy various fundamental properties that necessitate further evaluation.

The active region, including quantum wells and barriers, is the region where the laser action takes place. Although quantum wells are the main source of laser action, the quantum wells coupling is prevented by quantum barriers. Thus, quantum barriers are considered to be essential structural layers that affect the electrical, optical, and performance characteristics of GaN-based optoelectronic devices. Indium composition, doping concentration, and thickness of quantum barriers are the variable parameters that optimize their effects on output performance characteristics [6, 7]. Quantum barriers have significant effects on different recombinations in the active region including radiative and non-radiative recombinations. Among the various effective parameters for enhancing the performance of LDs, poor hole injection efficiency along with electron leakage is a critical factor. Several scientists have attempted to solve this problem by changing the laser structures [8, 9]. Hansen et al. proposed a thin AlGaN cap between the active region and p-type layers to avoid electron overflow [10]. The electron overflow is considerably reduced by utilizing this thin AlGaN layer which is known as an Electron Blocking Layer (EBL) [11-14]. Prior studies indicate that substituting the conventional GaN quantum barriers with the InGaN quantum barriers could effectively reduce polarization effects between the well and barrier and, then, decrease the electron current overflow [13]. Park et al. and Khan et al. demonstrated that optical properties

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URL: https://www.jree.ir/article_143144.html

Please cite this article as: Alahyarizadeh, Gh., Amirhoseiny, M. and Khorsandi, M., "Performance enhancement of deep violet InGaN double quantum wells laser diodes with quaternary superlattice barriers structure", ***Journal of Renewable Energy and Environment (JREE)***, Vol. 9, No. 1, (2022), 106-111. (https://doi.org/10.30501/jree.2021.300112.1246).

of InGaN MQWs could be enhanced with quaternary AlInGaN barriers [15, 16]. The use of quaternary AlInGaN provides an environment to control the lattice constant and bandgap. There are several EBL designs that are used to reduce electron overflow. They include AlInGaN quaternary EBL [17, 18], Strain-free GaN-InAlN SLS EBL [13], W-shaped EBL [19], step and linearly graded EBL [20], tapered and graded AlGaN EBL [21], quaternary AlInGaN/GaN SLS EBL [22], and quaternary AlInGaN multi quantum-barrier EBL [23]. In this regard, built-in polarization is also significantly reduced. Moreover, further designs have been proposed in the literature that use SLS cladding and waveguide layer instead of conventional cladding and waveguide layers [24, 25]. The proposed designs have improved OCF and consequently the output power. Furthermore, some approaches have been also proposed to enhance electron and hole wave functions overlapping in the active region including quantum wells and barriers. However, the performance improvement for InGaN- based LDs is still under process.

In this paper, we numerically compare the electrical and optical characteristics of InGaN MQW LDs with three different barriers structures. To enhance the emission intensity of the laser and reduce the threshold current, we have proposed the quaternary SLS structure on barriers. The performance of the GaN-based LDs can be investigated by analyzing the power characteristics, DQE, conduction, and valence energies in the vertical direction, electron and hole carrier densities, radiative recombination, and LD's optical emission intensity.

2. MATERIALS AND METHODS

The structural parameters such as thickness, material compositions, and doping type of basic LD structure, which is considered as a reference in this study, are given in Table 1. Except for the barriers, all the other layers in three desired LDs consist of the same layers compared to the basic structure. Barriers of LDs structure are replaced by a quaternary AlInGaN layer (structure B) and an AlInGaN/AlGaN superlattice (structure C), respectively. A diagram illustration of the LD structures is depicted in Figure 1.

Table 1. The structural parameters including thickness, material compositions, and doping type of basic LD structure

Component	Thickness (μm)	materials	Doping type
Base layer	0.4	GaN	n
Compliance layer	0.1	$In_{0.05}Ga_{0.95}N$	n
Cladding layer	0.42	$Al_{0.07}Ga_{0.93}N$	n
Waveguiding layer	0.1	GaN	n
Quantum wells (2)	0.0025	$In_{0.082}Ga_{0.918}N$	-
Quantum barriers (3)	0.0085	GaN	-
EBL	0.015	$Al_{0.22}Ga_{0.78}N$	p
Waveguiding layer	0.1	GaN	p
Cladding layer	0.42	$Al_{0.07}Ga_{0.93}N$	p
P-contact layer	0.1	GaN	p

The laser simulation process was performed by ISE-TCAD software. The simulation parameters are the same as those used in our previous studies [12, 26]. All the ternary and quaternary parameters were interpolated by binary alloys listed in Table 2.

Table 2. Room temperature properties of binary III-N materials [27]

Parameter	GaN	AlN	InN
Bandgap energy E_g (eV)	3.47	6.28	0.8
Electron affinity (eV)	4.1	1.9	5.8
Lattice constant a_0 (°A)	3.189	3.112	3.545
Refractive index near E_g	2.506	2.035	2.9
Electron effective mass	0.22 m_e	0.4 m_e	0.11m_e
Heavy hole effective mass	1.595 m_e	2.68 m_e	1.449 m_e
Light hole effective mass	0.261 m_e	0.261 m_e	0.157 m_e
spontaneous polarization Psp	-0.034	-0.090	-0.042
Elastic stiffness constant C_{13}(GPa)	106	108	92
Elastic stiffness constant C_{33}(GPa)	398	373	224
Relative dielectric constant	8.9	8.5	9.5

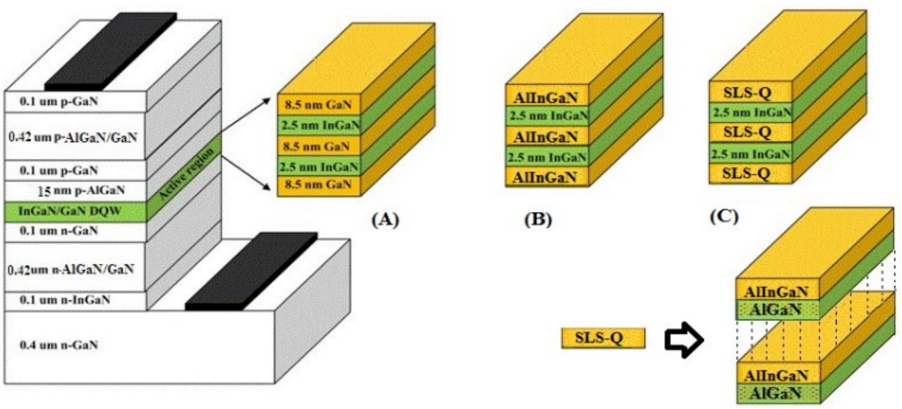

Figure 1. Illustration of InGaN MQW LDs including u-GaN (basic LD), AlGaN/GaN superlattice, and quaternary AlInGaN barri

3. RESULTS AND DISCUSSION

The threshold current, output power, slope efficiency, and Differential Quantum Efficiency (DQE) of the three different structures of deep violet $In_{0.082}Ga_{0.918}N$/GaN DQW LDs are shown in Table 3. Using quaternary AlInGaN barriers presents higher values for the output power, slope efficiency, and DQE, compared with the basic $In_{0.082}Ga_{0.918}N$/GaN DQW LD. Although quaternary barriers considerably enhanced the performance characteristics of LD, they would not decrease the threshold current remarkably. By replacing the barriers structure with AlInGaN/AlGaN quaternary SLS, LDs performance characteristics are still under significant progress compared to the basic structure, but the threshold current is considerably degraded. It can be introduced by comparing the conduction and the valence band energies of the proposed structure.

Figure 2 shows the conduction and valence band energies and the quasi-Fermi levels of the three different structures of deep violet $In_{0.082}Ga_{0.918}N$/GaN DQW LDs. As shown in Figure 2, the barrier structures are strongly affected by conduction, valance band, and the Fermi levels. The differences between conduction band energies and their quasi-Fermi levels can express the possibility of electrons leaking to the EBL layer to flow in the p-type layer. Finding a structure that can increase this difference would help to decrease the electron leakage and reduce the threshold current. On the other hand, the differences between valance band energies and their quasi-Fermi levels can define injection of holes to the active region and promote radiative recombination which would enhance the output power. The best structure should have both factors to improve the output power, slope efficiency, and DQE, whereas the threshold current is reduced.

The barrier's energy band is seriously affected by the built-in electric field induced by the compressive strain. The results show that in quaternary barriers, the electrons will confront a highly effective potential of 569 meV than the basic structure. At the same time, the holes encounter a much lower effective potential of about 123 meV. The higher effective potential between the conduction band and Fermi level decreases the threshold current in p-GaN and SLS barrier structures, as discussed in Table 1.

Table 3. The parameters of InGaN DQW laser with quaternary and SLS quaternary barriers structures

Parameter	Threshold current	Output power	Slop efficiency	DQE %	Wavelength
main:	16.59	33.49	1.627	51.29	390.667
MainQB:	15.01	40.59	1.882	59.17	389.640
All SLSQB:	12.88	39.05	1.860	58.40	389.294

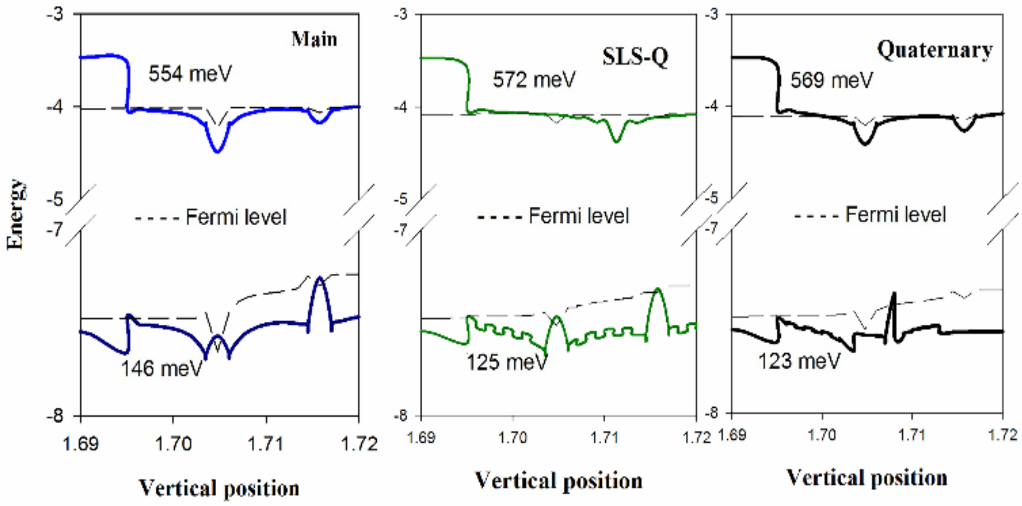

Figure 2. Energy band diagrams of InGaN DQW lasers with quaternary and SLS-Q barriers structures

A strong built-in polarization field due to the spontaneous polarization and a piezoelectric polarization field in the III-nitride structures are other parameters that affect the device's performance. A piezoelectric polarization field can be generated due to the lattice mismatch between different layers in the LD structure, especially between AlGaN and (In)GaN layers. This field can be reduced by using the AlInGaN layer or thin AlGaN, the GaN layer in the SLS structure (Figure 3). The built-in polarization field can pull down the GaN energy band and pull up the AlGaN ones, respectively. Therefore, the energy bands of AlGaN/GaN SLS barriers are bent. Thereupon, the height of the effective potential barrier for electrons increases and, then, the electron leakage is reduced. However, following the decreased effective potential, injection of the holes into the active region increases and consequently, the overall holes concentration also increases [**Error! Bookmark not defined.**]. The same trend can be seen in the carrier current densities in Figure 4.

It can be seen that the quaternary structure has the highest hole's current density in the active region among the other LDs. It is due to the improvement of the hole injection efficiency caused by the lowest effective potential height. Electron carrier density is another carrier that contributes to radiative recombination. As mentioned before, electron and hole leakages have an essential role in the reduction of the threshold current. The SLS barrier structure provides the lowest electron and hole leakage among the three recommended structures.

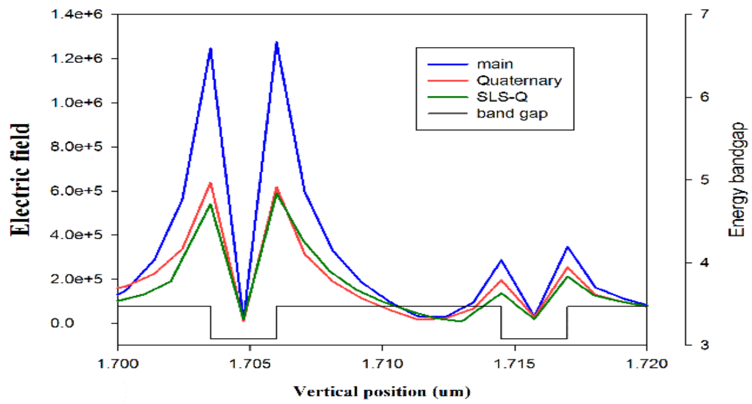

Figure 3. Electric field of InGaN DQW lasers with quaternary and SLS-Q barriers structures

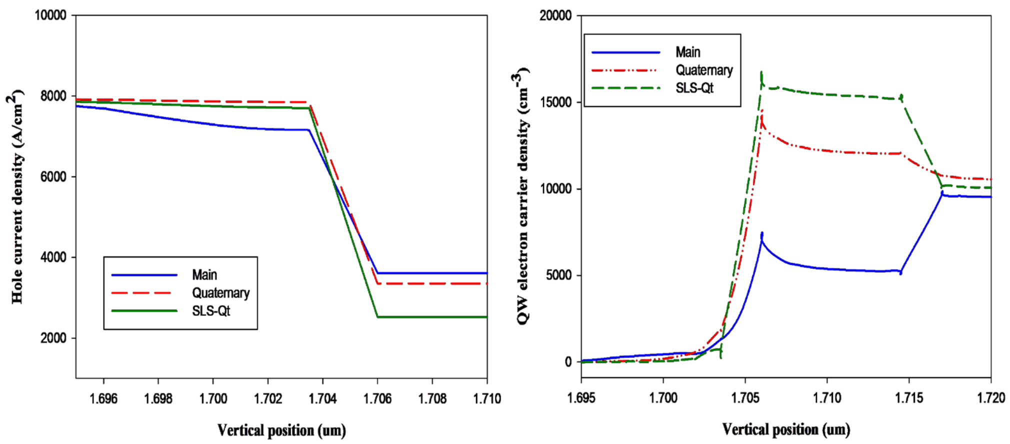

Figure 4. The carrier current density of InGaN DQW lasers with SLS and quaternary barriers structures

The radiative recombination rates of the three considered structures are shown in Figure 5. According to the knowledge that by increasing the carrier concentration, more electrons can remain in the active region which would be recombined with holes. Therefore, the efficiency degradation is reduced due to more quantum wells' contribution to the radiative recombination. As a result, it can be seen that the radiative recombination rate in quaternary and SLS-Q structures is higher than that in the basic structure because the two proposed structures provide greater extensive electron confinement and hole injection.

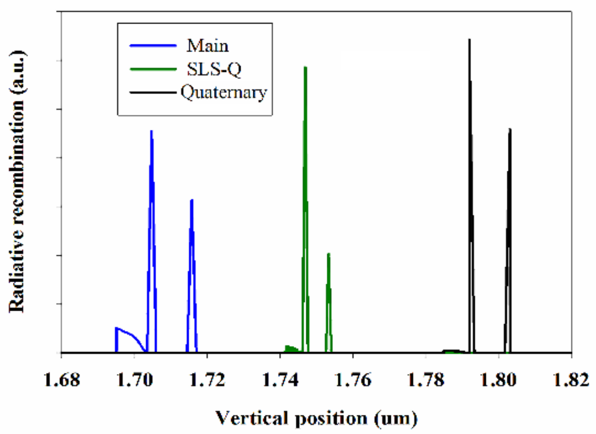

Figure 5. Rate of radiative recombination of the InGaN DQW lasers including quaternary and SLS-Q barriers structures

The optical intensity of the three of the InGaN DQW LDs with three different barriers structures is shown in Figure 6. The presence of more carriers in LDs that are supposed to accumulate in the active region improves the stimulated recombination rate in the active region and results in the enhancement of the optical intensity of LDs. It is observed that the InGaN laser with a quaternary structure has the highest carrier current density and good radiative recombination in the active region that causes the highest optical intensity among all the considered structures.

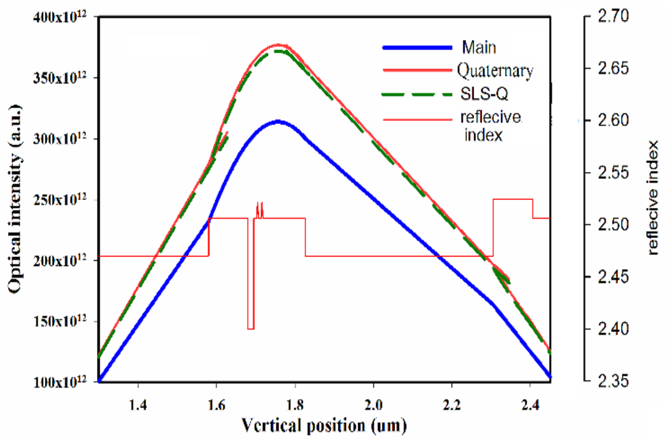

Figure 6. The optical intensity of the three structures of InGaN DQW lasers with quaternary and SLS-Q barriers structures

The light output characteristics of the InGaN DQW LDs with three different barrier structures are shown in Figure 7. As shown in this figure, the LD structures with quaternary and SLS-Q barriers have considerably higher output power than the main LD structures. The output power strongly depends on the photon density inside the cavity. Based on the presented results (Figure 2 & Figure 3), InGaN DQW LDs with quaternary and SLS-Q barriers are of highest current density, which itself indicates the highest amount of output power. The results of output power are completely in good agreement with the previously discussed outcomes and also with the reported experimental results in the literature [15].

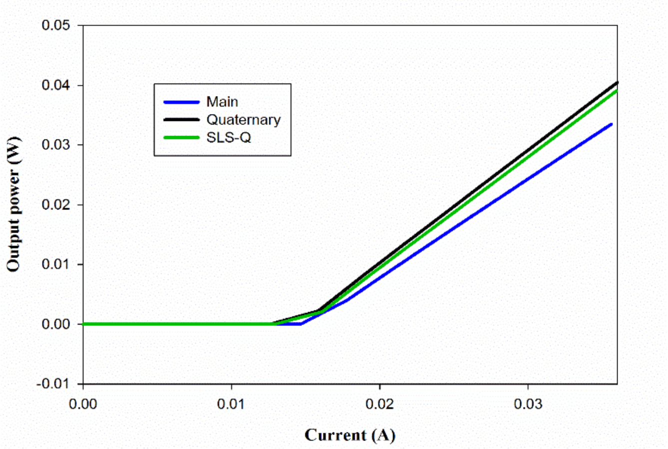

Figure 7. Light output characteristic (L-I) of InGaN DQW lasers with quaternary and SLS-Q barriers structures

4. CONCLUSIONS

To enhance the InGaN DQW LDs characteristics, a different designed LD was proposed with quaternary barriers and AlGaN/AlInGaN quaternary superlattice barriers. The simulation results indicate that the optical properties of the LDs were significantly enhanced in both quaternary and quaternary SLS structures owing to the increase of hole injection, the reduction of electron leakage, and the better radiative recombination in the QWs. Compared with the LDs using GaN, quaternary barriers, the laser with SLS-Q barriers exhibited the lowest threshold current. The reason could be the effects of the lowered generated strong piezoelectric polarization field due to the lattice mismatch between the AlGaN layer and the AlInGaN layer in the SLS structure. The proposed SLS-Q barriers, as the best structure, improved the output power, slope efficiency, and DQE while the threshold current was significantly reduced.

5. ACKNOWLEDGEMENT

The authors are gratefully indebted to Shahid Beheshti University for researching support of this work.

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